Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Contract Overview Report

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FOREWORD

This report was a product of the Federal Highway Administration's Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation's vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Lyle Saxton
Director, Office of Safety and Traffic Operations
Research
and Development

NOTICE

PRECURSOR SYSTEMS ANALYSES OF AUTOMATED HIGHWAY SYSTEMS
ACTIVITIES A, H, J, AND P

CONTRACT OVERVIEW REPORT

INTRODUCTION

Researchers from the member campuses of the California PATH Program have conducted research in four of the PSA Activity Areas. These research projects have been complementary to the extensive Automated Highway System (AHS) research already underway within the PATH Program, addressing topics that have not yet been addressed within the main body of the PATH research activities. The four PSA Activity Areas are:

A – Urban and Rural AHS Comparisons
H – Roadway Deployment Analysis
J – AHS Entry/Exit Analysis
P – Preliminary Cost/Benefit Factors Analysis

These four studies have been conducted largely independently because of considerable differences in the issues they are addressing and widely varying levels of depth versus breadth in their treatment of their topics. Similar reasons are behind different choices of Representative System Configurations (RSC) for the four studies. There have been some specific but limited interactions among aspects of the Activity H, J and P studies where these appeared to offer some real synergy.

The Activity A study is a very broad investigation of the issues that could serve to distinguish urban and rural implementations of AHS from each other. As such, it characterizes these AHS alternatives according to the following variables:

- Operating speed (100 or 150 km/hr) – 2 values
- Inter-vehicle spacing (10 or 20 m) – 2 values
- Demand – 3 levels
- Heavy vehicle strategy (mixed or segregated) – 2 cases
- Guideway configuration (mixed or separated from manual) – 2 cases
- Technological sophistication – 4 levels

The combination of all of these variables produces a matrix of 96 possible RSCs. Some of these were screened out as being unreasonable, leaving a total of 35 RSCs for more serious consideration. These were defined in considerably less detail than the RSCs that were needed for the other three studies.

At the opposite extreme, the Activity J study used a single RSC that has been defined in great detail as part of the PATH research program over a period of several years. In this study, five different geometric/operational configurations for AHS entry and exit were studied using queuing analysis and a very sophisticated AHS micro-simulation program, SmartPath. The RSC for this study is a high-capacity AHS operating in exclusive lanes installed in the median of existing freeways, with light-duty vehicles only. These fully automated vehicles operate in platoons, and intelligence is distributed in a hierarchical fashion as defined by Varaiya and Shladover.[1]

The Activity P study defined RSCs to focus specifically on an evolutionary sequence for the development and implementation of AHS, capturing the different levels of functionality that would be available at different times. These include (in addition to "basic" vehicle and roadway types such as already exist):

Vehicle types–
- ARV (AHS Ready Vehicle)
- AHS 1 (automated driving except for lane changing)
- AHS 2 (fully automated, including lane changing)

Roadway types–
- Roadway–vehicle communication
- Lane references for automatic steering
- AHS 1 (automated lanes separated from manual)
- AHS 2 (automated lanes adjacent to manual)

Intelligence distributions–
- Infrastructure intensive
- Minimum infrastructure modifications

Traffic operations–
- Mixed traffic
- Dedicated AHS lanes.

Activity H has concentrated attention on differences in the ways the AHS roadway infrastructure could be provided, without much regard for differences in vehicle operating assumptions. It assumes fully automated AHS operations, in lanes that are separated from manual lanes either by use of a transition lane with barriers or totally segregated with independent access ramps. The different roadway deployment configurations included:

- AHS lanes added in existing median space
- AHS lanes added in median, with mixed flow lanes expanded on outer edges of existing pavement
- AHS lanes on separate structure elevated above freeway median
- AHS lanes in tunnel beneath existing freeway.

These RSCs were developed in order to serve the specific needs of the individual activity area studies, which were quite different from each other. This enabled each study to make the maximum contribution in its own topic area, rather than forcing it to compromise with the other studies that have very different needs. The opportunities for synergy among the different activity area studies were limited, but were exploited to the extent possible. These included:

- AHS entry/exit geometric configurations were shared between entry/exit and roadway deployment studies, so that both infrastructure and operational considerations could be factored into both studies;

- Roadway configurations defined in roadway deployment study were used as baseline for developing cost estimates in cost/benefit study;

- Both roadway deployment and cost/benefit study used the same case study corridor, U.S. Highway 101 (Hollywood Freeway) in Los Angeles, so that conceptual design work and costing could be done using the same detailed data about the existing roadway infrastructure.

Beyond these limited examples, it appeared that further attempts to impose common assumptions across the four studies would be detrimental rather than beneficial.

TECHNICAL FINDINGS IN EACH ACTIVITY AREA

Activity A – Urban and Rural AHS Comparisons

- AHS Systems optimized for very different traffic demand densities are likely to be substantially different from each other. This means that some compromises will be needed to devise systems that are interoperable between urban and rural applications.

- The selection of maximum operating speed and the decision whether to include heavy vehicles within the AHS design have different implications for the urban and rural settings. These will have significant impacts on the physical design of the AHS infrastructure and on its energy and environmental effects.

- The benefits of AHS appear to be more significant in the urban areas, particularly where congestion is a serious issue, and in the more advanced stages of AHS development where there could be significant capacity improvements.

- The net economic impact of AHS appears to be favorable across the board, but there are concerns about the equity of distribution of that impact.

- The entirely vehicle-based AVCS services that are likely to precede fully functional AHS do not raise issues that would produce contrasts between urban and rural AHS. However, once we reach the level of requiring roadway infrastructure and TMC investments, the differences between urban and rural applications become important issues.

Activity H – Roadway Deployment Analysis

- The specific issues affecting the feasibility and cost of AHS roadway deployment are highly localized and dependent on a variety of physical constraints. For this reason, a general analysis of the issues would not really be applicable, but rather a case study for a specific setting was found to be much more appropriate.

- Even in the most challenging case study corridor that could be identified in California, there were only moderate infrastructure constraints to the deployment of new AHS lanes. This means that in the large majority of California freeway settings it should be relatively easy and inexpensive to add AHS lanes.

- Where physical constraints were found, it was still possible to devise viable infrastructure deployment alternatives. The most difficult conditions were encountered at freeway-to-freeway interchanges, particularly where there were left-lane merges and splits on the existing freeways, which tend to interfere with the placement of AHS-exclusive lanes to the left of the conventional lanes.

- The roadway deployment alternatives that were explored are:

(1) At-grade lane conversion with shared roadway geometry, in which AHS traffic enters and exits AHS lanes through a transition lane. In this case, all access must also include entering and exiting the existing freeway through its normal on and off ramps. That saves the cost of constructing new ramps, but tends to limit throughput and potentially reduces safety (because of numerous lane changes).

(2) At-grade lane conversion with new dedicated entry/exit facilities. In this case, the construction of the new on and off ramps increases cost but improves throughput and safety and minimizes interactions with the existing freeway. It may also require some additional right-of-way to make space for the ramps, and could limit access to the automated lanes by emergency vehicles when incidents occur.

(3) Above-grade construction of segregated AHS facility. This raises issues of construction cost, seismic safety, visual and noise impacts to the adjacent neighborhoods and access by emergency vehicles. However, it has significant safety and throughput advantages because of the total segregation from manual traffic. In high density locations where there is no space remaining within the freeway right of way, land is expensive and widening of the freeway would require reconstruction of overpasses and retaining walls and relocation of utilities, this is likely to be the lowest cost alternative.

(4) Below-grade construction of segregated AHS facility. This is ordinarily the most costly, and raises issues of ventilation and utility relocation. However, it may be necessary for limited lengths at older complicated freeway-to-freeway interchanges in physically constrained locations.

- Although most attention was devoted to urban settings, three rural corridors were also evaluated and, not surprisingly, found to be much less challenging than the urban settings because of the availability of ample space for segregated at-grade facilities.

<u>Activity J – AHS Entry/Exit Analysis</u>

- Automated and manual vehicles must be kept segregated from each other in the interest of safety. Erratic behavior of manual vehicles could force accidents with automated vehicles.

Only automated vehicles must be permitted to enter the automated lanes, and their entry must be coordinated with the movements of the vehicles already traveling in the automated lanes.

- Barriers are needed between automated and manual lanes, so that accidents in the manual lanes cannot spill over into the automated lanes. The higher density of traffic in the automated lanes would cause such an accident to be more severe than accidents occurring today (involving more vehicles).

- The entry of vehicles into an automated lane must be regulated in order to avoid disrupting the flow of traffic on the automated lane. When automated traffic flow is heavy, there is a potential risk of entering vehicles not being able to find an opening in the traffic stream for a long time. This would require a very long, costly transition lane. This problem can be resolved if the entering vehicles are stopped and then "released" at the proper time to coordinate their arrival at the entry point to the automated lane with the arrival of a suitable gap in the automated flow. This requires a queuing space at the entry ramp or transition lane, but this should be considerably shorter than the space that would be required if vehicles did not stop.

- Provisions must be made for removing an exiting vehicle from the transition lanes if its driver is unable to resume control. Otherwise, the vehicle would block the exit or the incapable driver could cause collisions with other vehicles in the transition or manual lanes. Providing space for accommodating these vehicles is one of the more challenging AHS entry/exit issues.

- Longitudinal spacings between entering vehicles and the vehicles already traveling in the automated lane must be controlled carefully in order to minimize hazards. If these vehicles are very far away (implying very light traffic), there is no problem. If they are very close together (entering immediately at the end of a platoon), the danger is much less than if they operate at intermediate spacings, where an abrupt deceleration of the preceding vehicle is likely to cause a serious crash.

- Automated vehicles exiting the automated lane into a transition lane must be coordinated with the movements of the vehicles in the transition lane. This means that the vehicles in the transition lane must be capable of communicating with the automated vehicles, thereby prohibiting manual vehicles from traveling in the transition lane.

- A transition lane may be divided into segments, one per entry and exit. Although this may not be a significant issue in high-density urban settings, where entry and exit locations are very close together, it is relevant in lower-density areas, with longer spacings between AHS access points.

- Providing access to automated lanes from dedicated ramps simplifies the coordination of entry and exit maneuvering but may increase roadway construction costs. The trade-off between dedicated ramp and transition lane access is complicated and the economics are heavily site-specific, making it impractical to draw general conclusions.

- It is not clear whether a continuous breakdown lane is needed. While it would tend to make it easier to gain access to and route traffic around a failed vehicle, it comes at a heavy infrastructure cost. This cost is high enough that it is worthwhile considering other alternatives, such as barriers that can be removed or crossed by emergency vehicles or special design emergency vehicles that could access failed vehicles by unconventional means.

Activity P – Preliminary Cost/Benefit Factors Analysis

- It will be very desirable for vehicle manufacturers to develop an "AHS Ready Vehicle" with steering, throttle and brake actuators, flexible user interface, safety diagnostics, adaptive cruise control and lane tracking capabilities as a basis for stand-alone commercial products. If these are widely sold to the public (AVCS driver warning and control assistance user services), significant economies of scale could be enjoyed for much of the AHS vehicle capabilities.

- As an example for an annual production rate of 1,000,000 vehicles in the year 2002, the AHS Ready Vehicle would cost about $2000 more than a conventional vehicle, while the AHS capabilities would add about an additional $1500 to the cost.

- If the AHS Ready Vehicle is introduced in the year 2000, it would not be likely to reach a fleet penetration of 20% before 2009 or 50% before 2014. Since it would provide benefits to purchasers driving on any roadways, it should be expected to have a much larger market than the fully AHS equipped vehicles. The AHS add-on capabilities would be options that would only be available in those cities where AHS roadways are constructed.

- For the case study highway (U.S. Highway 101 in and near downtown Los Angeles), where there is no room to expand the existing highway right of way, the least expensive method for adding AHS lanes is to build an elevated structure with dedicated on/off ranps, at a cost of $17.5 million per km (with one AHS lane in each direction). In less constrained locations, the cost of providing additional AHS lanes will be significantly lower.

- The cost of converting existing lanes to AHS is much less than the cost of constructing entirely new lanes (on the order of $300,000 per km).

- For the case study highway location, the cost for the added capacity of the AHS 1 service (without automatic lane changing) is comparable to the cost for a conventional highway expansion that would provide the same capacity increase. For AHS 2, with its higher capacity, the cost is potentially 25% less.

- Looking ahead to the year 2020, high capacity AHS appears to be most viable in a select group of six major metropolitan areas with serious congestion, high land values, and high incomes. These areas could require 7500 lane-km of AHS roadway, which would be used to 25 to 40 million vehicles (roughly 10% of the fleet in 2020).

- On a national basis, annual cost savings for the 7500 lane-km systems, would amount to $4.5 billion per year for the higher capacity AHS 2 system (representing a 5% annual return on a

$21 billion investment, deferred 25 years). Savings appear to be negligible for the lower capacity AHS 1.

- The uncertainties are much larger for the vehicle costs than for the infrastructure costs because most of the roadway costs are for relatively conventional construction work rather than for technologies that are not yet mature.

OVERALL CROSS-CUTTING OBSERVATIONS

These four studies have addressed diverse aspects of the very broad subject of Automated Highway Systems. Because of this diversity, the cross-cutting observations must remain rather general:

- There do not appear to be any insurmountable obstacles to AHS implementation in general, even in some of the most difficult settings in California.

- The AHS design and configuration must be tailored to the needs and constraints of the specific implementation location. This is likely to lead to great diversity in the physical infrastructure implementations of AHS.

- The infrastructure costs of AHS implementation are likely to be much more heavily weighted towards traditional construction cost items such as structural and paving materials and labor than towards high-technology or electronics. These latter are likely to be much more prominent on the vehicles.

- The AHS design and operating strategies to be implemented should be heavily dependent on the performance goals that are established for the system. This is particularly the case for the desired capacity, which could vary significantly from one location to another.

- Despite potentially very different local goals, conditions and constraints, it will be necessary to have standards for interoperable AHS throughout the country. This will probably require compromises among diverse interests, but will be necessary in order to make it practical for manufacturers to develop the vehicles and for customers to acquire the vehicles with confidence that they can be used widely.

REFERENCES

1. Varaiya, P., and S.E. Shladover. "Sketch of an IVHS Systems Architecture," Vehicle Navigation and Information Systems Conference Proceedings, Paper No. 912838, Dearborn, MI, October 1991, pp. 909-928.