Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Cost/Benefit Analysis

Volume I: Cost/Benefit Analysis of Automated Highway Systems

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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

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EXECUTIVE SUMMARY

The objective of this activity is to develop a framework for the evaluation of alternative AHS deployment concepts, with respect to life-cycle costs and benefits. This framework is applied to a range of scenarios, to capture benefits and costs on both a highway and national basis. The study uses results of the best available benefits studies, and creates original AHS cost estimates.

Focus of Effort

In addition to producing the evaluation framework, this activity helps identify the types of locations that would benefit most from AHS, as well as strategies for evolutionary deployment. Specific features of the activity include:

- Evolutionary approach to AHS development, using the catalyst of AHS Ready Vehicles (ARVs), and installation of low-cost infrastructure to support automatic steering on inter-city highways (documented in volume II).
- Original cost estimates for both the vehicle and infrastructure, under a range of operating scenarios, including infrastructure-intensive and vehicle-intensive system configurations. Elemental roadway costs are based on a specific implementation along the U.S. 101 freeway in Los Angeles (volumes III and IV).
- Review of studies on AHS benefits and impacts (volume VI).
- Formal assessment of risks and uncertainties, based on techniques of subjective probability assessment and decision analysis. This risk assessment is used to provide a probabilistic estimate for the range of uncertainty (volume V).
- Comparison of the cost-effectiveness per unit capacity for AHS to alternative highway investments (volume I).
- Extrapolation of results to a national scale, to account for scale economies in vehicle production and AHS investments (volume I).

Overall Approach

The study was divided into five phases: (1) development of system configurations and evolutionary deployment strategy; (2) engineering cost estimation; (3) survey of AHS impacts; (4) risk analysis; and (5) cost/benefit synthesis. These are discussed below.

System Configurations System configurations were developed in two steps, by first developing an evolutionary deployment strategy on a functional basis, and then identifying specific technologies to accomplish the functions. The evolutionary development strategy consists of three steps, including AHS Ready Vehicles, AHS without automated lane change, and AHS with automated lane change. Evolutionary deployment is critical for the following reasons:

- To develop a critical mass of instrumented vehicles prior to extensive infrastructure deployment.

- To allow technologies to be tested and refined in less rigorous low-volume conditions.

- To exploit scale economies, by creating a market for low-end instrumented vehicles throughout the United States, prior to extensive infrastructure deployment, thus lowing the cost for fully automated vehicles.

- To accrue benefits at intermediate steps of deployment.

The evolutionary scenarios were combined with two electronics implementation scenarios, one vehicle intensive (referred to as "minimum infrastructure modification", or MIM) and the other infrastructure intensive (II). In addition, various roadway scenarios were created, based on site specific construction considerations.

Cost Estimation Cost estimation included the identification of major cost drivers, for electronics and construction, and life-cycle based cost estimation. Cost estimates were made by consulting experts in various technological domains, and projecting future costs from cost reduction curves (accounting for reduced electronics costs over time). Because site characteristics can add considerably to construction costs, elemental construction cost estimates were produced for a specific highway (U.S. 101, Los Angeles), which possesses a range of conditions that might be experienced on an AHS. This task was coordinated with activity area H, performed by PATH.

Impact Survey and Assessment AHS impacts (benefits or dis-benefits) were assessed from both a system and a user perspective, based on a survey of the AHS literature. This approach was critical, because any realistic deployment path must provide benefits exceeding costs to both the user and society to justify individual investment in vehicle equipment, and government investment in infrastructure Reviews of individual studies are provided in volume VI, and a summary is provided in this volume.

Risk Analysis The risk analysis identified the major uncertainties, and quantified their effect on costs. These uncertainties included vehicle electronics cost and roadway construction cost, as well as other factors described in volume V. Percentile estimates were created through interviews with specialists on the cost/benefit team, utilizing using formal probability assessment techniques. These techniques were also used to develop three-point probability distributions for each key parameter. The analysis then developed a simplified framework delineating relationships and dependencies among parameters and overall cost/benefit measures.

Cost Effectiveness The cost effectiveness of AHS, as a means for augmenting capacity, was evaluated by comparing AHS costs to conventional roadway expansion strategies. This was evaluated on a highway segment basis, accounting for both roadway costs and vehicle costs.

Cost/Benefit Synthesis The study concluded with the task of synthesizing the results from the cost analysis and benefit assessment into the broad cost/benefit evaluation framework. The task was directed at extrapolating benefits from single locations to a national scale.

Guiding Assumptions

The study made no attempt to determine the feasibility of implementing AHS, at either the technical or institutional level. Instead, we have explored the costs and benefits of alternative AHS configurations, under the assumption that these configurations perform as anticipated. It should be borne in mind that different configurations have different likelihoods of success and, therefore, minimizing anticipated cost and maximizing anticipated benefits are not the only objectives.

A second premise of the study was that some AHS benefits are difficult to predict because they depend on how future drivers respond to new AHS technologies. This is especially true of delay reduction. There does not currently exist any verified model for forecasting changes in demand patterns which may result from increased highway capacity, let alone AHS capacity. With potential capacity increases of a factor of 2 or 3 under AHS, changes in trip length and frequency, mode choice, trip generation rates, and so on are certain to be significant, and must be factored into any accurate estimate of changes in delay.

The study adopted a methodology that allows for quantification of capacity benefits but circumvents the above pitfall. This was accomplished through the evaluation of benefits on a relative basis, by comparison to conventional means of adding capacity. Evaluations were performed by estimating cost as a function of capacity added, taking into account site characteristics and the number of vehicles that must be AHS equipped in order to support an AHS facility.

The perspective of the study is that AHS can become one of many options for solving congestion problems in cities. Whether AHS is used or not may hinge on its cost-effectiveness relative to conventional alternatives. Specifically, the question of whether or not to build an AHS may hinge on whether the space saving aspect of AHS (due to higher capacity per lane) offsets any cost increases that may come from more complicated construction, or from installation of electronics in the vehicle or on the roadside. At the same time, side benefits from AHS, which may come from improved vehicle performance (which may lead to energy savings and pollution reductions), were also documented.

Conclusions

- For the year 2002, with 1,000,000 vehicles in production, the 7 year life cycle costs are as follows: $2,068 for AHS Ready Vehicle (ARV), $3,412 for AHS1 (high capacity, with manual lane change) and $3,498 for AHS2 (high capacity with automated lane change; all measured in 1994 dollars, assuming infrastructure intensive systems). The range of uncertainty in these estimates is roughly -70% to +50%.

- For the case study highway (U.S. 101 in Los Angeles), the least expensive method for adding lanes is to provide an elevated structure with dedicated on/off ramps, at $17.5 million/km.

- AHS Ready Vehicles (ARVs) are unlikely to reach a fleet penetration of 20% before 2009 and unlikely to reach a fleet penetration of 50% before 2014, based on 2000 as the year of introduction.

- For the year 2020, high capacity AHS appears to be most viable in a select group of cities, reasonably amounting to 7,500 lane-kilometers, supported by 25-40 million vehicles (roughly 10% of the fleet in 2020).

- It would be difficult to attain scale economies in AHS1 or AHS2 without the simultaneous sale of ARVs. ARVs could reasonably be marketed nationwide, while AHS1 and AHS2 equipment could be customer options, available in those cities where high capacity AHS roadways are constructed.

- Annual cost savings, based on 7,500 lane-kilometers, amount to $2.3 billion per year for AHS2. This represents a 5% annual return on a $11 billion investment, deferred 25 years. For both AHS1 and AHS2, cost estimates contain considerable uncertainties.

ACKNOWLEDGMENTS

Sidharth Chandramoulli, David Lotspeich, and Ashish Saboo of the University of Southern California contributed to this report. Cost analyses were performed by Rockwell International and Bechtel, and the risk analysis was performed by Lawrence Livermore National Laboratories.

CHAPTER 1. INTRODUCTION

The objective of this activity is to develop a framework for the evaluation of alternative AHS deployment concepts, with respect to life-cycle costs and benefits. This framework is applied to a range of scenarios, to capture benefits and costs on both a highway and national basis. The study uses results of the best available benefits studies, and creates original AHS cost estimates.

1.1 Specific Focus of Effort

In addition to producing the evaluation framework, this activity helps identify the types of locations that would benefit most from AHS, as well as strategies for evolutionary deployment. Specific features of the activity include:

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- Original cost estimates for both the vehicle and infrastructure, under a range of operating scenarios, including infrastructure-intensive and vehicle-intensive system configurations. Elemental roadway costs are based on a specific implementation along the U.S. 101 freeway in Los Angeles (volumes III and IV).

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- Comparison of the cost-effectiveness per unit capacity for AHS to alternative highway investments (volume I).

- Extrapolation of results to a national scale, to account for scale economies in vehicle production and AHS investments (volume I).

1.2 Issues Addressed in Activity Area

The cost/benefit activity produces original cost estimates, as well as a general framework for cost/benefit analysis. Specific issues addressed include:

- Vehicle and infrastructure electronics cost,
- Roadway construction and electronics installation,
- User benefits (congestion,safety,energy,performance,etc.),
- Systems benefits (congestion,pollution,safety,energy,etc.),
- Risk analysis,
- Operating and maintenance costs.

User and system benefits are based on a review of prior research, while all cost estimates are original to this study.

1.3 Overall Approach

The study was divided into five phases: (1) development of system configurations and evolutionary deployment strategy; (2) engineering cost estimation; (3) survey of AHS impacts; (4) risk analysis; and (5) cost/benefit synthesis. These are discussed below.

System Configurations System configurations were developed in two steps, by first developing an evolutionary deployment strategy on a functional basis, and then identifying specific technologies to accomplish the functions. The evolutionary development strategy consists of three steps, including AHS Ready Vehicles, AHS without automated lane change, and AHS with automated lane change. Evolutionary deployment is critical for the following reasons:

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- To allow technologies to be tested and refined in less rigorous low-volume conditions.
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Impact Survey and Assessment AHS impacts (benefits or dis-benefits) were assessed from both a system and a user perspective, based on a survey of the AHS literature. This approach was critical, because any realistic deployment path must provide benefits exceeding costs to both the user and society to justify individual investment in vehicle equipment, and government investment in infrastructure. Reviews of individual studies are provided in volume VI, and a summary is provided in this volume.

Risk Analysis The risk analysis identified the major uncertainties, and quantified their effect on costs. These uncertainties included vehicle electronics cost and roadway construction cost, as well as other factors described in volume V. Percentile estimates were created through interviews with specialists on the cost/benefit team, using formal probability assessment techniques. These techniques were also used to develop three-point probability distributions for each key parameter. The analysis then developed a simplified framework delineating relationships and dependencies among parameters and overall cost/benefit measures.

Cost Effectiveness The cost effectiveness of AHS, as a means for augmenting capacity, was evaluated by comparing AHS costs to conventional roadway expansion strategies. This was evaluated on a highway segment basis, accounting for both roadway costs and vehicle costs.

Cost/Benefit Synthesis The study concluded with the task of synthesizing the results from the cost analysis and benefit assessment into the broad cost/benefit evaluation framework. The task was directed at extrapolating benefits from single locations to a national scale.

1.4 Guiding Assumptions

The study made no attempt to determine the feasibility of implementing AHS, at either the technical or institutional level. Instead, we have explored the costs and benefits of alternative AHS configurations, under the assumption that these configurations perform as anticipated. It should be borne in mind that different configurations have different likelihoods of success and, therefore, minimizing anticipated cost and maximizing anticipated benefits are not the only objectives.

A second premise of the study was that some AHS benefits are difficult to predict because they depend on how future drivers respond to new AHS technologies. This is especially true of delay reduction. There does not currently exist any verified model for forecasting changes in demand patterns which may result from increased highway capacity, let alone AHS capacity. With potential capacity increases of a factor of 2 or 3 under AHS, changes in trip length and frequency, mode choice, trip generation rates, and so on are certain to be significant, and must be factored into any accurate estimate of changes in delay. Furthermore, any study which fails to account for these changes would overestimate percentage reductions in delay, and would present a biased representation of future benefits.

The study adopted a methodology that allows for quantification of capacity benefits but circumvents the above pitfall. This was accomplished through the evaluation of benefits on a relative basis, by comparison to conventional means of adding capacity. Evaluations were performed by estimating cost as a function of capacity added, taking into account site characteristics and the number of vehicles that must be AHS equipped in order to support an AHS facility.

The perspective of the study is that AHS can become one of many options for solving congestion problems in cities. Whether AHS is used or not may hinge on its cost-effectiveness relative to conventional alternatives. Specifically, the question of whether or not to build an AHS may hinge on whether the space saving aspect of AHS (due to higher capacity per lane) offsets any cost increases that may come from more complicated construction, or from installation of electronics in the vehicle or on the roadside. At the same time, side benefits from AHS, which may come from improved vehicle performance (which may lead to safety improvements, energy savings and pollution reductions), were also documented.

1.5 Report Organization

The remainder of the final report is divided into six chapters. Chapter 2 describes the system configurations upon which the analysis is based. Chapter 3 summarizes elemental cost results, along with the risk analysis. Chapter 4 summarizes benefits results. Chapter 5 evaluates the cost-effectiveness of capacity expansion. Chapter 6 provides the cost/benefit synthesis, which extrapolates results to a nationwide scale. Chapter 7 provides conclusions.

The final report is supplemented by the five volumes listed below:

Volume II: System Configurations, Evolutionary Deployment Considerations
Volume III: Electronics Cost Methodology and Cost Estimates
Volume IV: Roadway Infrastructure Cost Methodology and Cost Estimates
Volume V: Analysis of Automated Highway System Risks and Uncertainties
Volume VI: Review of Studies on Automated Highway System Benefits and Impacts

CHAPTER 2. REPRESENTATIVE SYSTEM CONFIGURATIONS

This chapter provides a condensed description of the system configurations used in the cost/benefit analysis. Configuration details and criteria can be found in volume II: System Configurations, Evolutionary Deployment Considerations.

To satisfy criteria outlined in volume II, it is desirable to build up a critical mass of AHS equipped vehicles prior to extensive deployment of AHS infrastructure. We propose accomplishing this goal through the development and sale of an "AHS Ready Vehicle" (ARV). An ARV is modularly designed, allowing easy installation, after point of sale, of supplemental sensors and communication devices. Its controller is re-programmable, either via software or plug-in replacement of integrated circuits, to respond to additional sensor and communication inputs. At point of sale, the ARV possesses electronic steering, braking and throttle control; a flexible driver interface; safety diagnostics; adaptive cruise control; automated steering capabilities (the latter of which can only function on designated inter-city highways on which the driver can reasonably resume control if required.). The ARV is capable of operating on a fully automated highway if retrofitted. An ARV also provides immediate driver benefits, in the forms of comfort and performance.

From the standpoint of roadway infrastructure, we propose that AHS be first deployed on low-volume roadways connecting urban centers. The "Auto-steering AHS" would provide a lane referencing system, which would enable ARVs to operate in a fully automated mode with large inter-vehicle spacing. These initial forms of AHS would not provide capacity gains, but would, at relatively modest cost, motivate ARV sales. They would also provide an opportunity for testing and refining AHS technologies, prior to their deployment under more demanding conditions.

2.1 Evolutionary Strategy

Building from the catalysts of the AHS Ready Vehicle, and the Auto-Steering AHS, the evolutionary strategy is filled out below, from the vehicle and roadway perspectives. At any point in time, we recognize that the fleet of vehicles operating in the United States will contain a mixture of capabilities, falling into four stages:

Vehicle Types

(1) Basic: No automation capabilities (other than basic cruise control), and no possibility of retrofit for automation.

(2) ARV: Possesses adaptive cruise control and drive-by-wire, and can be retrofitted for full automation at reasonable cost.

(3) AHS1: Able to operate in fully automated mode under high volume, but not able to automatically change lanes.

(4) AHS2: Able to operate in fully automated mode, and to change lanes under full automation.

In addition, at any point in time, the United States highway system will contain a mixture of roadway types, categorized into the following five stages:

(1) Basic: Conventional highway, with IVHS functions limited to ramp-metering, loop-detectors and changeable message signs (at most).

(2) Roadway-Veh Comm: Roadway-vehicle communication is provided, primarily to support traveler advisory and route planning functions, but upgradeable to support AHS.

(3) Auto Steer: In addition to roadway-vehicle communication, a lane referencing system is installed to support automated steering. Fully automated driving is allowed for low volume roadways.

(4) AHS1 driving: AHS lanes are physically isolated from conventional, and fully automated for automobiles and light trucks and vans under high volume conditions is enabled. Automated inspection is provided. Automated lane changing is not supported.

(5) AHS2 Automated lane-change and lane merging is provided. Furthermore, automated lanes do not have to be completely isolated from conventional.

This study is primarily concerned with stages 2-4 under vehicle types and stages 3-5 under roadway types.

2.2 Technological Implementation

The evolutionary strategy is the basis for specific technological implementations, which were used for cost analysis purposes. These implementations were guided not so much by feasibility, as by a desire to bracket costs and benefits from above and below. At each stage of evolution, system configurations were developed along the following two lines (summarized in table 1; see section 3 for more detail).

Vehicle-Intensive and Infrastructure Intensive With respect to electronics (including sensors, communication and control), a vehicle intensive (MIM -- minimum infrastructure modification) and an infrastructure intensive (II) scenario were developed. The MIM scenario uses minimal communication, and places most of the sensing capabilities on the vehicle, relying heavily on on-board video-image-processing. The infrastructure intensive scenario utilizes vehicle-vehicle communication to reduce sensing requirements, and moves some of the sensing capabilities from the vehicle to the roadside. The MIM scenario is further subdivided according to mixed traffic versus dedicated lanes.

Roadway Construction A range of scenarios was created for roadway construction, including: (1) All lanes allow mixed traffic; (2-4) automated lane at grade with existing highway; and (5) elevated highway with complete separation of automated vehicles. The most cost-effective scenario is likely to be highly site specific, depending on available un-used right-of-way, and existing roadway characteristics.

CHAPTER 3. COST ANALYSIS

The cost analysis is divided into three sections, covering electronics cost, roadway construction cost and cost risk analysis. Each section is documented more fully in an independent volume (III-V).

3.1 Electronics Cost Analysis

The major costs for vehicle owners are due to the increased amount of electronics required by the system. These electronics control the braking system, throttle, and steering, as well as provide the sensors and computational capacity to perform required control tasks. Possible electronics which are required for the more advanced systems include vision sensors, increased computational speed and memory for the sensory processing unit, and a more complex unit for self-tests and

Table 1. Applicability of roadway scenarios to electronics scenarios

	ELECTONICS SCENARIOS						
	Mixed Traffic			----------Dedicated Lanes---------			
				---Min Infrastructure Mod----		Infra. Intense	
Roadway Scenarios	**ARV**	**AHS1**	**AHS2**	**AHS1**	**AHS2**	**AHS1**	**AHS2**
(1) All Lanes Allow Automated	X	X	X				
(2) 1 Auto + 1 Buffer				?	X	?	X
(3) 1 Auto + 1 Buffer + dedicated ramps				X	?	X	?
(4) 1 Auto, No Buffer				?	?	?	?
(5) Dedicated Facility				X	?	X	?

Legend

X: Roadway Scenario is Definitely Applicable to Electronics Scenario

?: Roadway Scenario is Possibly Applicable to Electronics Scenario

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*Alternately, some subset of the lanes might allow automated vehicles.

diagnostics due to reduced fault tolerances for either AHS1 or AHS2 systems. AHS2 systems additionally require sensors such as vision sensors capable of covering the 360 degrees around the car to check for lane changes, a driver interface capable of accepting off-ramp selection from the driver, a protocol for lane selection and navigation to the desired off-ramp, and a means for vehicle to vehicle communication as well as vehicle to traffic management system communication. Volume III details these costs for each system and also discusses the expected infrastructure electronics and upgrade costs. Table 2 lists the additional purchase cost associated with each vehicle system and a variety of production years and production quantities. 7-year support (i.e., maintenance) cost is provided in table 3, to complete a life-cycle estimate. In both tables, the year of production shows the falling cost due to competitive effects and technology advancements, while the production quantity is used to examine possible economies of scale. A 20 percent annual reduction is assumed for electronics, and a 10 percent annual reduction is assumed for mechanical components (both measured in constant dollars).

Electronics infrastructure costs for the various systems are shown in table 4 for each year of production. These numbers all tend to be small, based on an optimistic projection that the system can rely on inexpensive vision sensor units. The cost for such units has dropped considerably in recent years. However, it remains unclear whether the type of units envisioned will suffice (details in volume III). *Hence, the numbers provided may significantly underestimate the true cost.*

Figure 1 shows the estimated total cost (both purchase and seven year support) at year 2002 with 1,000,000 in production. These numbers range from $2,068 for the ARV to $5,030 for a minimal-infrastructure vehicle in mixed traffic, under AHS2. Note especially that costs are considerably lower for infrastructure-intensive (II) implementations, especially under AHS2, without adding considerably to infrastructure cost. *Hence, the II implementation is adopted within system based analyses that appear later*. It should be noted that these costs are considerably less than the estimates for 1998 and 2000, and less than estimates for lower production volumes. Hence, the numbers would be substantially higher in the absence of technology advances and scale economies, and may be lower in later years.

The upgrade costs from the ARV to more advanced systems and from AHS1 to AHS2 systems are shown in table 5. These numbers are significant to determining the viability of evolutionary development. Note that an ARV vehicle can be upgraded to AHS1 (infrastructure intensive, 2002, 1,000,000 volume) for $1,689 and to AHS2 for $2,011. Hence, the total installation cost, counting an initial ARV purchase price of $1,397, amounts to $3,086 for AHS1 and $3,408 for AHS2. These numbers are roughly $1,000 above the cost of having AHS1 and AHS2 installed as original equipment.

It is impossible to judge whether these costs are sufficiently small to motivate ARV purchasers to upgrade to operate on high-capacity AHS1 or AHS2 facilities. However, even without upgrade, ARV can play an important role. A large population of ARV purchasers would result in scale economies in production of key AHS components (especially actuators), which will lower the cost of AHS1 and AHS2 vehicles. Hence, production of ARV vehicles may be essential to eventual adoption of fully automated vehicles.

Table 2. AHS vehicle electronics purchase costs

1998

Scenario	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 3,575	$ 2,858	$ 2,450	$ 2,291
AHS1, Mixed Traffic, Min. Infrastructure	$ 7,650	$ 6,057	$ 5,141	$ 4,807
AHS2, Mixed Traffic, Min. Infrastructure	$ 9,356	$ 7,398	$ 6,271	$ 5,864
AHS1, DL, Min. Infrastructure	$ 6,413	$ 5,090	$ 4,332	$ 4,051
AHS2, DL, Min. Infrastructure	$ 7,919	$ 6,274	$ 5,330	$ 4,983
AHS1, DL, Intensive Infrastructure	$ 6,501	$ 5,159	$ 4,391	$ 4,106
AHS2, DL, Intensive Infrastructure	$ 6,957	$ 5,518	$ 4,693	$ 4,388

2000

	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 2,735	$ 2,193	$ 1,886	$ 1,763
AHS1, Mixed Traffic, Min. Infrastructure	$ 5,301	$ 4,205	$ 3,578	$ 3,345
AHS2, Mixed Traffic, Min. Infrastructure	$ 6,392	$ 5,064	$ 4,301	$ 4,021
AHS1, DL, Min. Infrastructure	$ 4,565	$ 3,633	$ 3,100	$ 2,899
AHS2, DL, Min. Infrastructure	$ 5,529	$ 4,390	$ 3,739	$ 3,496
AHS1, DL, Intensive Infrastructure	$ 4,622	$ 3,677	$ 3,138	$ 2,934
AHS2, DL, Intensive Infrastructure	$ 4,914	$ 3,907	$ 3,331	$ 3,115

2002

	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 2,154	$ 1,732	$ 1,494	$ 1,397
AHS1, Mixed Traffic, Min. Infrastructure	$ 3,757	$ 2,988	$ 2,549	$ 2,384
AHS2, Mixed Traffic, Min. Infrastructure	$ 4,456	$ 3,538	$ 3,012	$ 2,816
AHS1, DL, Min. Infrastructure	$ 3,338	$ 2,664	$ 2,280	$ 2,132
AHS2, DL, Min. Infrastructure	$ 3,955	$ 3,149	$ 2,689	$ 2,514
AHS1, DL, Intensive Infrastructure	$ 3,374	$ 2,692	$ 2,304	$ 2,154
AHS2, DL, Intensive Infrastructure	$ 3,561	$ 2,839	$ 2,428	$ 2,270

DL refers to Dedicated Lanes for Automated Vehicles

Table 3. AHS vehicle 7 year support cost summary

1998

Scenario	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 2,650	$ 2,072	$ 1,728	$ 1,533
AHS1, Mixed Traffic, Min. Infrastructure	$ 9,687	$ 7,350	$ 5,968	$ 5,326
AHS2, Mixed Traffic, Min. Infrastructure	$ 12,940	$ 9,789	$ 7,927	$ 7,069
AHS1, DL, Min. Infrastructure	$ 6,735	$ 5,140	$ 4,196	$ 3,750
AHS2, DL, Min. Infrastructure	$ 8,919	$ 6,781	$ 5,516	$ 4,925
AHS1, DL, Intensive Infrastructure	$ 6,384	$ 4,882	$ 3,992	$ 3,571
AHS2, DL, Intensive Infrastructure	$ 6,077	$ 4,661	$ 3,820	$ 3,419

2000

	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 1,671	$ 1,321	$ 1,112	$ 1,003
AHS1, Mixed Traffic, Min. Infrastructure	$ 5,364	$ 4,097	$ 3,347	$ 2,993
AHS2, Mixed Traffic, Min. Infrastructure	$ 7,064	$ 5,376	$ 4,375	$ 3,909
AHS1, DL, Min. Infrastructure	$ 3,827	$ 2,946	$ 2,422	$ 2,170
AHS2, DL, Min. Infrastructure	$ 4,973	$ 3,809	$ 3,119	$ 2,791
AHS1, DL, Intensive Infrastructure	$ 3,652	$ 2,818	$ 2,322	$ 2,083
AHS2, DL, Intensive Infrastructure	$ 3,503	$ 2,713	$ 2,242	$ 2,013

2002

	1000	10000	100000	1000000
AHS Ready Vehicle(ARV)	$ 1,091	$ 873	$ 741	$ 671
AHS1, Mixed Traffic, Min. Infrastructure	$ 3,041	$ 2,344	$ 1,929	$ 1,730
AHS2, Mixed Traffic, Min. Infrastructure	$ 3,934	$ 3,017	$ 2,473	$ 2,214
AHS1, DL, Min. Infrastructure	$ 2,239	$ 1,742	$ 1,445	$ 1,299
AHS2, DL, Min. Infrastructure	$ 2,844	$ 2,200	$ 1,816	$ 1,630
AHS1, DL, Intensive Infrastructure	$ 2,153	$ 1,680	$ 1,398	$ 1,258
AHS2, DL, Intensive Infrastructure	$ 2,084	$ 1,633	$ 1,363	$ 1,228

DL refers to Dedicated Lanes for Automated Vehicles

Table 4. Infrastructure electronics costs

Infrastructure Costs per 100 kilometers of Roadway
by year of acquisition for each scenario

Scenario	1998	2000	2002
AHS1, DL, Intensive Infrastructure	$306,461	$196,981	$125,866
AHS2, DL, Intensive Infrastructure	$490,563	$315,551	$201,528

Infrastructure 20 Year Support Costs per 100 kilometers of Roadway
by year of acquisition for each scenario

Scenario	1998	2000	2002
AHS1, DL, Intensive Infrastructure	$1,447,478	$783,254	$674,491
AHS2, DL, Intensive Infrastructure	$2,451,704	$1,351,309	$1,182,484

Table 5. ARV electronics upgrade costs per vehicle

From:	ARV	ARV	AHS1
To Scenario	2000/10,000	2002/1,000,000	2002/1,000,000
AHS1, Mixed Traffic, Min. Infrastructure	$3,235	$1,839	N/A
AHS2, Mixed Traffic, Min. Infrastructure	$4,518	$2,568	$1,863
AHS1, DL, Min. Infrastructure	$2,581	$1,551	N/A
AHS2, DL, Min. Infrastructure	$3,749	$2,222	$1,486
AHS1, DL, Intensive Infrastructure	$2,745	$1,689	N/A
AHS2, DL, Intensive Infrastructure	$3,265	$2,011	$1,124

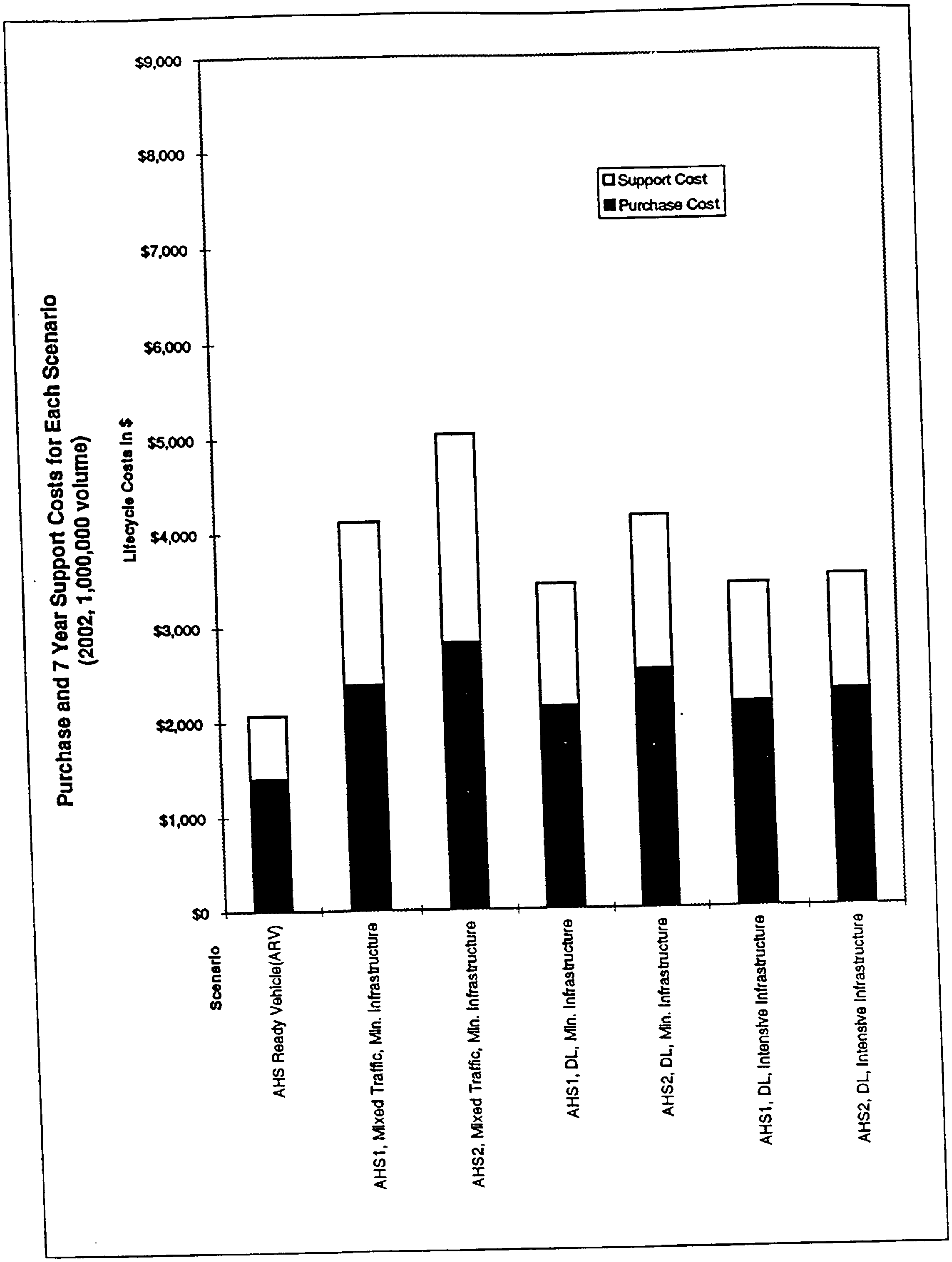

Figure 1. Vehicles electronics cost by scenario

3.2 Roadway Construction Cost Analysis

Roadway construction options are discussed at length in volume IV. Five options are studied, as follows:

(1) Instrumenting all highway lanes, and not segregating AHS traffic from conventional traffic.

(2) Adding a buffer lane that can be used by both automated and non-automated traffic and converting the left-most lane into an AHS lane.

(3) Adding a buffer lane and converting the left-most lane to AHS, along with segregating these lanes from conventional traffic. The buffer and AHS lanes are accessed by dedicated on/off ramps from bridges.

(4) Converting one lane into an AHS lane, which is delimited by paint stripes and rumble strips.

(5) Adding an elevated structure for AHS traffic with its own dedicated on-ramps and off-ramps.

Note that only options 3 and 5 completely segregate AHS traffic from conventional traffic. Hence, AHS1, as defined earlier, is only applicable to these two options.
Cost analysis was based on a specific 16 kilometer highway segment: U.S. 101 (Hollywood Freeway), running north from Downtown Los Angeles. The highway has four lanes in each direction, and is characterized by numerous over-crossings, narrow right-of-way and dense construction immediately surrounding the right-of-way. There are currently 92 total structures, 18 on-ramps and 18 off-ramps in the northbound direction and 19 on-ramps and 21 off-ramps in the southbound direction. In other words, the roadway is typical of the difficult construction conditions inherent to locations where AHS is envisioned. It is not representative of suburban locations, where construction costs are likely to be considerably smaller.
The cost analysis is based on competitively bid Caltrans projects, for the first quarter of 1994. All estimates include a 10% mobilization and 20% contingency. Maintenance cost is also not included, under the assumption that costs would be comparable to conventional roadways. Right-of-way acquisition is priced at $25 per square foot. The number of dedicated AHS on/off ramps is approximately equal to the number of conventional on/off ramps. The costs also do not allow for direct freeway to freeway connections from the AHS lanes, for options 3 and 5.

Table 6 provides a summary cost comparison of the five options. Construction management cost (approximately 15% of cost) is not included in table 6, but is included in sections 5 and 6. Most noteworthy is that the cost of installing roadway electronics (incorporated in options 1 and 4) is small relative to constructing additional lanes. Option 4, for instance, amounts to approximately $300,000/km. Option 3, on the other hand, is the most expensive option, amounting to nearly $24,000,000/km. Important conclusions follow:

Table 6. Roadway construction cost summary

AUTOMATED HIGHWAY SYSTEM – SUMMARY OF COST ESTIMATES		07-LA-101-0.0/10.0				
Item	Description	Option 1	Option 2	Option 3	Option 4	Option 5
01	Mass Earthwork	0	6,033,333	8,283,333	0	5,000,000
02	Retaining Walls	0	19,008,000	21,600,000	0	5,184,000
03	Bridges	0	65,877,200	83,886,800	0	149,320,000
04	Pavement	0	13,027,680	14,755,680	0	215,200
05	Soundwalls	0	6,652,800	6,652,800	0	0
06	Landscaping and Erosion Control	0	1,000,000	1,000,000	0	0
07	Pedestrian and Bicycle Facilities	0	250,000	400,000	0	100,000
08	Signalization and Lighting	0	3,000,000	5,250,000	0	2,250,000
09	Drainage and Creek Channel Improvements	0	5,000,000	7,700,000	0	2,250,000
10	Barrier and Guard Railing	0	2,084,000	4,421,000	0	225,000
11	Signage	150,000	3,000,000	3,450,000	150,000	450,000
12	Striping	0	2,000,000	2,180,000	528,000	380,000
13	Construction Support and Detours	2,220,000	17,084,000	21,584,000	1,120,000	21,584,000
14	Existing Facilities – Remove, Salvage, Relocate, etc	0	10,000,000	10,450,000	0	5,000,000
15	Utility Relocation incl in Construction Contract	0	15,000,000	15,900,000	0	5,000
16	Other Itemized Costs	4,490,000	6,850,000	7,225,000	1,850,000	4,225,000
Subtotal		6,860,000	175,867,013	214,738,613	3,648,000	196,188,200
17	Mobilization	686,000	17,586,701	21,473,861	364,800	19,618,820
Total Bid Level Cost		7,546,000	193,453,714	236,212,474	4,012,800	215,807,020
18	State Furnished Materials and Expenses	300,000	4,000,000	4,500,000	50,000	4,000,000
Subtotal		7,846,000	197,453,714	240,712,474	4,062,800	219,807,020
19	Contingency	1,569,200	39,490,743	48,142,495	812,560	43,961,404
Total Construction Cost		9,415,200	236,944,457	288,854,969	4,875,360	263,768,424
20	Land Acquisition	0	51,490,000	67,690,000	0	16,200,000
21	Utility Relocation	0	25,000,000	27,250,000	0	2,250,000
Total Right-of-way Cost		0	76,490,000	94,940,000	0	18,450,000
Total Construction Cost plus Right-of-way Cost		9,415,200	313,434,457	383,794,969	4,875,360	282,218,424

- If additional lanes are needed, it is much less expensive to build an elevated structure (option 5) than to add lanes at the level of the existing highway. This is primarily due to reduced land acquisition cost and reduced need for retaining walls. However, if direct connections are required at freeway-freeway interchanges, option 2 might become more attractive.

- If AHS can be implemented without adding lanes, cost is reduced enormously (to only $300,000/km under option 4). However, this is likely feasible only in later stages of automation, under AHS2, after fleet penetration exceeds 25% (ensuring that sufficient capacity remains for conventional vehicles). In earlier stages, new lanes may have to be constructed at considerable cost ($17.5 million/per center-line KM under option 5).

- ARV infrastructure can be installed at minimal cost, on the order of $50,000/km for magnets. Hence, cost does not appear to be a serious deterrent to developing automatic steering capabilities on inter-city roadway.

3.3 Cost Risk Analysis

The objective of the risk analysis was to formally analyze the uncertainty associated with cost estimates. The basic steps of the methodology follow:

(1) Select cost/benefit factors for risk assessment.

(2) Develop percentile estimates for each key factor through interviews with specialists (creating a "subjective probability" distribution).

(3) Develop a simplified framework delineating relationships and dependencies among parameters and overall cost/benefit factors.

(4) Implement the risk analysis model on a personal computer for convenient sensitivity analysis.

Details of the methodology can be found in volume V. Here, we emphasize key findings with respect to vehicle electronics and roadway construction costs. These results illustrate the types of uncertainties inherent to cost estimation, which can be formally analyzed through risk assessment techniques.

Initial interviews revealed some of the most significant uncertainties. (In the following, "point estimate" refers to the estimates incorporated in tables 2-6). These include:

Multi beam millimeter radar and vision-based sensor initial costs While the costs of most vehicle components were estimated using catalogue prices of similar items or actual engineering experience, these two key sensor costs were developed using a parametric cost prediction model (PRICE), where existing equivalent systems were not in production. Inputs to the PRICE model required forecasting such things as weight and technology for production subassemblies. An “initial cost multiplier,” or icm variable, was defined for PRICE estimated sensors to quantify uncertainty in these initial costs.

Time improvement parameter (TIP). This is the yearly price reduction factor (point estimate of 20 percent per year for electronics and 10 percent per year for electro-mechanical) used to model how economic competition and technology improvements lower the cost of products over time.

Brake and steering actuator initial costs. These electro-mechanical products were estimated from discussions with an owner/operator of a local automobile repair business rather than from catalogues. An “initial cost multiplier” or icm variable was defined for these actuators to quantitatively express uncertainty in these initial costs.

For roadway construction, the specifications based directly on the specific freeway selected (U.S. 101) were accepted in the risk analysis and not second-guessed as to how typical such situations might be elsewhere. However, even with this specific roadway, there were significant uncertainties:

Retaining Walls Percentage of the project length (point estimate of 25 percent) that would require retaining walls.

Sound Walls Percentage of the project length (point estimate of 30 percent) that would require sound walls.

Drainage and Creek Channel Improvements These costs were computed for other options relative to Option 2. The latter had some uncertainty regarding the magnitude (point estimate of $5M) of the costs.

Utility Relocation Included in Construction Contract Allowance per kilometer (point estimate of $2.41M).

Land Acquisition Right-of-Way Costs Cost per square foot (point estimate of $25).

Land Area Required for Interchanges Average size required (point estimate of 1 acre).

Utility Relocation Allowance per 16 km (point estimate of $25M).

It turns out that none of these seven variables is relevant to options 1 and 4, and thus these options are based entirely on point estimates. Only drainage/creek channel improvement and land acquisition right-of-way cost uncertainties are relevant to option 5, and the risk analysis takes this into account.

Overall, the risk analysis did not address potential cost items not explicitly modeled. The potential for additional cost categories, which might not even be anticipated today, adds to the underlying risk. Hence, the true uncertainty is likely to be greater than the results that follow.

Table 7 provides the resulting uncertainty estimates for vehicle electronics, applied to year 2002 with a production volume of 1,000,000/year. Table 8 is similar, but applied to roadway construction. Within the table, the point estimate is the initial "best guess," as reported in volume III and section 3.1. All other numbers are derived from the interviews, which produced probability distributions for various costs. These numbers are expressed as percentages, relative to the point estimates.

It is important to note that the mean of the probability distribution can differ from the point estimate because the mean takes into account the full distribution of possible costs. Perhaps most significant in the tables are the ranges between the 5th and 95th percentile estimates, which are
anywhere from a 4:1 to 5:1 ratio for vehicle costs, and anywhere from 1:1 to 1.15:1 ratio for roadway construction. As discussed in volume V, the greatest source of the vehicle cost uncertainty is the annual electronics price reduction factor, estimated to be 20%/year.

It is interesting that among the three roadway options that require added lanes, option 5, which creates a dedicated structure, has the least uncertainty (largely because land requirements and costs are highly predictable). However, it is clear that, in a relative sense, the electronics cost is the greater source of uncertainty. Overall, it is not surprising that the risk analysis indicates notable uncertainties in vehicle costs. At this point in time, a risk analysis which did not show much uncertainty would not be credible.

CHAPTER 4. IMPACT AND BENEFIT ANALYSIS

The impact/benefit analysis is based on a review of 25 published reports, and 11 ongoing studies under the AHS PSA program. Volume VI reviews each of these studies in detail, with respect to system concept, impacts studied, methodology, assumptions and findings. It should be borne in mind that these studies vary considerably in scope, methodology, and quantification of impacts and benefits. At one extreme, studies by General Motors and Miller (PATH) are documented in several volumes, and include detailed analyses. On the other extreme, several studies only speculate on possible impacts, without quantification or methodology.

4.1 Review by Impact Area

This chapter reviews the results by impact area. For each impact area, relevant studies are described, along with key findings and major uncertainties.

Air Quality/Environment AHS has the potential for reducing air pollution in three ways: by improving engine control, smoothing traffic flows, and reducing aerodynamic drag on platooned vehicles. However, there might also be an increase in vehicles kilometers traveled as a result of AHS. Evidence to date is inconclusive as to whether AHS would result in a net increase or

Table 7. Vehicle electronics cost uncertainties
(relative to 2002, 1,000,000 volume point estimate)

	Mixed Traffic			Dedicated Lane			
		MIM		MIM		II	
	ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
Grand Mean	85%	79%	78%	81%	79%	81%	80%
Grand SD	38%	39%	41%	37%	39%	38%	39%
<u>Percentile</u>							
5th	37%	25%	21%	31%	26%	31%	29%
95th	161%	153%	154%	153%	153%	153%	154%

Table 8. Roadway construction cost uncertainties
(relative point estimate)

	Roadway Construction Option				
	1	2	3	4	5
Grand Mean	100%	108%	108%	100%	102%
Grand SD	0%	9.4%	9.3%	0%	2.6%
<u>Percentile</u>					
5th	100%	94%	94%	100%	98%
95th	100%	124%	124%	100%	106%

decrease in pollution. Studies suggest that when congestion is eliminated, significant increases in traffic volume can be accommodated while maintaining a net reduction in pollution. This result does not take into account pollution reductions due to improvements in engine control, for which benefits have not yet been documented. A final factor, likely to have a marginal effect, could be changes in vehicle weight, especially if electronic controls replace their hydraulic counterparts.

Barth (1) used a power demand-based modal emissions model to estimate total AHS emissions. Barth concluded that at an average speed of 48 km/hr and a traffic volume of 2053 veh/hr, an automated lane produces 50 percent less emissions than a manual lane, and that for a given level of emissions, an AHS could carry twice as much traffic as a conventional lane.

Miller et al (2) evaluated the impacts of roadway electrification and automation on air quality through the application of SCAG's (Southern California Association of Government) planning model to the Los Angeles region, for various deployment scenarios. Sizable air quality improvements and petroleum usage reductions were observed. However, Miller's study did not account for the potential for AHS to induce more travel. Johnston and Ceerla (3), on the other hand, did consider induced travel in their planning studies for the Sacramento region. This was accomplished through a cycling process, in which travel time reductions were fed back to trip generation and distribution models. Their study predicts that increases in vehicle miles traveled may result in increased emissions overall. In both studies, the pollution models employed were more macroscopic than used in Barth's work.

Shladover (4) discusses how technological improvements in automobiles can reduce the transportation's contribution to global warming while satisfying people's desire for mobility and economic development. An integrated approach is recommended for solving the problems of congestion, safety, energy, air quality and global climate change.

Zabat (5) found that reductions in aerodynamic drag associated with platooning could reduce air pollution per kilometer traveled. He found that drag reductions are on the order of 40 percent, based on 4 vehicle platoons at 1/2 car length spacings.

Capacity Increased capacity is a primary objective of AHS. Prior studies have investigated vehicle-following control rules (e.g., platooning vs. non-platooning), inter-vehicle spacing, vehicle performance characteristics (rates of acceleration and deceleration, and response time) and presence/absence of barriers between lanes, all as determinants of capacity.

In one line of research, the SmartPath AHS simulator was developed to investigate these questions. Rao et al (6) and Tsao et al (7) have estimated the achievable capacity of an AHS, accounting for lane change effects. Rao et al (6) found that high on-ramp flows of up to 1800 veh/hr can be supported, while a peak flow rate of 6,000 veh/hr per lane can be achieved. Similar results were obtained in Tsao et al's work, which also investigated the effect of lane barriers, and compared platooning against non-platooning. Tsao et al found that barriers resulted in capacity reductions of up to 20 percent, and platooning increased capacity by up to 20 percent. Rao and Varaiya (8) evaluated the performances of adaptive cruise control. Throughput was found to be as large as 5,500 vehicles/hour per lane, though this dropped to 2,700 vehicles per hour because of fluctuations in the transition lane.

In addition to simulations, capacity has been investigated through use of analytical models [7,9]. For instance, Hall examined throughput effects on multi-lane AHS resulting from lane-changes accessing left-most lanes. In between analytical models and discrete simulations, Rao and Varaiya [10] developed a fluid based simulation model to investigate the effects of "link layer" controls on stream stability, as well as the ability of the AHS to respond to incidents. Finally, Ward [11] provides a conceptual evolution of an AHS, and analyzes capacity changes resulting from "spontaneous platooning."

Overall, while the theoretical capacity for an AHS might be as high as 8,000 vehicles per lane per hour, evidence to date suggests that the actual capacity, once accounting for lane changes, is no more than 6,000 vehicles per lane per hour, and perhaps less than 5,000 vehicles per lane per hour if barriers are used and/or platooning is not employed. Major uncertainties include whether platooning is acceptable to users, and whether vehicle controls will be as effective in practice as they are assumed within simulations.

Community Impacts The impacts of AHS on surrounding communities has not been studied in any great depth (Al-Ayat and Hall [12] provide some discussion, but no analysis). There is the potential for visual impact, should elevated structures be used. Entrances, exits and lane additions might also require some taking of adjoining land, though an explicit goal of AHS is to minimize this impact. There are also potential noise and pollution impacts (discussed elsewhere). General Motors [13] discusses potential community disruption due to AHS, including right-of-way acquisition, increased traffic volumes in some locations and changes in infrastructure (statistics are provided). In general, however, the impacts should be similar to those of conventional highways, with the exception that AHS should occupy less space.

Energy Impacts on energy consumption are similar to those on air pollution. Improved engine control and traffic flow, and reduced aerodynamic drag, can act to reduce consumption, while induced demand can act to increase consumption. Zabat [5] states that reduced aerodynamic drag may result in a 20-25 percent energy savings. General Motors [13] also examined energy consumption characteristics of AHS vehicles and aggregated these measures via energy utilization equations. Otherwise, no in-depth analyses have been completed to date.

Land Requirements While an AHS could improve throughput per lane, and perhaps reduced lane width land requirements for AHS, land requirements are still not negligible. For instance, space requirements for check-in and check-out facilities are potentially significant. GM [13] states that AHS land requirements are such that more land is necessary where not enough is available, as in congested city centers. Hall [14] examines land requirements for parking, and observes that these may greatly exceed those for the freeway itself, especially in densely developed business districts. He also notes that savings in land requirements for AHS are small relative to total highway size. On the other hand, he notes that AHS may enable highway capacity to be augmented in locations where no realistic alternative exists, as when highways are surrounded by buildings or other structures.

Mobility/Congestion Already mentioned previously, the studies by Miller et al [2] and Johnston and Ceerla [3], investigate the effects of AHS on congestion within the Los Angeles and Southern California regions, respectively. In the Miller study, congestion mitigation was observed in general, while mobility deterioration was noticed on existing freeway ramps. However, this deterioration might well have been mitigated through re-design of these ramps. Johnston and Ceerla's study accounted for induced travel, which acted to moderate reductions in vehicle hours of delay. Chira-Chavala (15) evaluated the effects of longitudinal control technologies on traffic operation and highway capacity. This study estimated an increased flow rate if AICC is used. However, flow rate may be sensitive to platoon size.

Hall (14) examined the travel time benefits of automated highways, focusing on delay reductions at highway bottlenecks. According to this study, an AHS with automated low-speed merging can reduce queuing and delay substantially, even with low operating speeds. "Mini-highways", situated along narrow right-of-ways, may also lead to reductions in highway access time, which could further reduce congestion on arterials.

While the effects of AHS on congestion are still uncertain, it appears reasonable to expect that it would result in a net reduction in delay per vehicle on AHS equipped highways, along with parallel arterials. Access roadways and on-ramps and off-ramps may experience increased delay, unless their capacity is augmented. However, if AHS are built as stand-alone facilities, this problem would be mitigated, because traffic would be diverted from the vicinity of existing on-ramps and off-ramps.

Noise impacts come from increased traffic volumes and speeds. No study has explicitly examined these impacts for AHS, though they are unlikely to be different from conventional highways. Johnston et al (16) recommend the investigation of freeway sound walls to reduce noise pollution.

Performance/Features/Comfort AHS has the potential for improving driver comfort, through relief of the driving task. Electronic steering, braking and throttle control can also potentially lead to improved vehicle performance (i.e., more responsive braking characteristics, improved handling, and improved acceleration). For the most part, these benefits have not yet been analyzed.

Bonnano et al (17) investigated the market penetration of automated vehicles based on the experience of vanpoolers. This study postulated that vanpool characteristics may be extrapolated to AHS, because they share the common benefit of "chauffeured driving." Most individuals in their study had a strong preference for not driving. However, the demand for automation could depend on other factors, such as safety, comfort, ease of operation and cost.

Pricing/Equity AHS would only be accessible to equipped vehicles, which would tend to favor higher income drivers, along with owners of newer vehicles. This might be perceived as inequitable. However, to the degree that AHS attracts vehicles from other roadways, congestion is mitigated for non-AHS travelers. In addition, charging a toll to recover construction and operating cost might mitigate equity concerns. Pricing and equity issues have not been investigated in depth, though they are discussed in Johnston et al (16).

Safety/Reliability Safety is of extreme importance in AHS because of their reliance on as of yet unproved technologies, and the potential for human interference in system operation.

Safety problems for an automated highway are quite unlike those on ordinary roads. Most accidents today are due to human error, which are greatly reduced by automation. However, automation may produce new types of accidents, or perhaps contribute to accidents through more demanding operating conditions (especially, with shorter average inter-vehicle spacings). Therefore, accident records on existing roads do not shed enormous light on AHS safety. Studies to date have examined potential AHS faults, which could lead to collisions, as well as the consequences of collisions (severity and follow-on collisions).

Anwar and Jovanis (18) assess the safety consequences of mainline freeway accidents on the operation of an AHS in the highway median. Accidents of interest are those in which vehicles or debris are propelled across the freeway toward the automated lane. The authors conclude that these accidents represent a significant risk to the viable operation of the AHS. This is one of the motivations for the installation of barriers on highways, to ensure that debris is physically prevented from entering the AHS.

Hitchcock (19) states that platoon join maneuvers cause unnecessary dangers and suggests remedial measures. However, platoon split maneuvers are not dangerous. The mean time between failures of control system should be at least 10^6 hours in order to ensure reliability. This study assumes a platoon size of 8, traveling at a velocity of 110 km/hr. Hitchcock (20) proposes the development of safety criteria for AHS, along with techniques to ensure that the safety criteria are met.

A probabilistic model and software tool for analyzing longitudinal collisions between automated vehicles was developed by Tsao and Hall (21). A safety comparison is made between platooning and the "free-agent" configuration. While platooning has the beneficial effect of reducing the relative velocity of vehicles at initial impact (thus reducing accident severity), it also greatly increases the frequency of minor collisions. If these low "delta velocity" collisions lead to subsequent impacts, then platooning could be less safe than free agent. Tongue and Yang (22) are concerned with the dynamics of platoons under emergency situations. A concept of "back control" is introduced. Four different platoon scenarios have been examined.

Safety is a major focus of several ongoing PSA studies. For example, USC/Raytheon (23) propose an evolutionary path with extensive reliability studies. It treats vehicles as "packets of data". Findings include that sensors may improve safety is general, while automated systems need to be more reliable than the systems they replace.

In a general sense, safety remains one of the major uncertainties for AHS. These uncertainties may only be resolved after extensive testing and refinement of the operating systems. In particular, it is highly uncertain whether automated vehicles will be able to safely operate in mixed traffic with conventional vehicles.

4.2 Assessment of Benefits by Scenario

While much has been learned about the possible benefits and impacts of AHS, the state of research is such that it is only possible to distinguish between stages of evolution (i.e., ARV, AHS1 and AHS2), and not between technological implementations (i.e., MIM vs. II). With this in mind, the following discusses benefits and impacts of the three stages of AHS evolution: ARV, AHS1, and AHS2. These three stages offer significantly different lane capacities, as discussed below and in tables 9-11.

AHS Ready Vehicle Primary benefits come in the form of improved comfort and performance, and accompanying energy savings. There may also be safety benefits, through the introduction of collision avoidance and warning devices. All of these benefits can occur on or off an AHS facility. Only the auto-steering function requires infrastructure investments. On the other hand, there are safety risks in operating the ARV in fully automated mode, even under low volume conditions, because vehicle sensors may be unable to detect normal hazards and the driver may not be sufficiently attentive to take over control when required.

AHS1 AHS1 provides an incremental capacity benefit over ARV. The magnitude of the capacity increase is somewhat limited, however, due to the necessity for manual merging and exiting from lanes. We assume that close headway platooning is employed on AHS1, with large gaps between platoons. These large gaps enable vehicles to manually enter and exit the automated lane without disrupting traffic flow, resulting in capacity increases. However, manual lane changes would necessarily subtract from capacity, due to the large space occupied during execution of lane change maneuvers. We estimate that the capacity for AHS1 is 4,000 vehicles/hour per lane, which is approximately 50 percent of the theoretical maximum capacity (8,000 vehicles/hour, with platoon sizes of 15, intra-platoon spacing of 1m and inter-platoon spacing of 90m). The 50 percent reduction is approximate, assuming that a lane change takes approximately 30s to execute (counting joining and exiting a platoon) and occupies 125m of lane space during execution (derived from Hall [10]).

AHS1 provides additional benefits in the forms mentioned for ARV. There is also the potential for safety improvements while operating on the AHS1 facility, as well as energy and pollution reductions, due to reduced congestion. However, because AHS1 augments capacity, some of these benefits may be reduced due to increases in traffic. Furthermore, there are significant safety risks for configurations in which automated vehicles are mixed in traffic with conventional vehicles.

AHS2 We assume that automation enables vehicles to change lanes into, and out from, smaller gaps, resulting in capacity gains over AHS1. Prior studies on AHS with automated lane change have estimated capacities on the order of 5,500 vehicles per lane per hour, which we adopt here.

AHS2 provides additional benefits in the form mentioned for ARV. There is also the potential for safety improvements while operating on the AHS2 facility, as well as energy and pollution reductions due to reduced congestion (which may be offset by increased traffic levels).

Table 9. Impacts and benefits of ARV

User Impacts	Discussion
Energy	Reductions due to electronic throttle control.
Mobility	No significant change.
Performance	Electronic control may improve handling,braking,responsiveness. AICC and auto-steering provide enhanced comfort.
Safety	Safety warnings may improve safety. Uncertain hazards when operating in an automated mode.
System Impacts	
Air Quality	Electronic throttle control may reduce emissions.
Capacity	No significant change.
Community	No significant change.
Energy	Electronic throttle control may reduce energy consumption
Land	No significant change.
Mobility	No significant change.
Noise	No significant change.
Pricing/Equity	No significant change. Means for recovering the cost of installing the lane referencing is an issue.
Safety	Uncertain risks. Collision warning may improve safety in some conditions, but operating in fully automated mode in mixed traffic, with low volume, poses uncertain risks.

Table 10. Impacts and benefits of AHS1

User Impacts	Discussion
Energy	Reductions due to electronic throttle control, and reductions per kilometer due to reduced congestion on AHS1 equipped facilities.
Mobility	Improvements due to reduced congestion on AHS1 equipped facilities and on parallel arterials.
Performance	Electronic control may improve handling,braking,responsiveness. AICC, auto-steering and AHS1 provide enhanced comfort.
Safety	Safety warnings may improve safety. Uncertain hazards when operating in an automated mode.
System Impacts	
Air Quality	Electronic throttle control and improved traffic flow should reduce emissions per kilometer traveled. These reductions may be offset by increased kilometers traveled.
Capacity	Increase to 4,000 vehicles/hour on AHS1 facilities. No changes elsewhere.
Community	Possible impacts in immediate vicinity of AHS1 facilities, similar to that of conventional highways.
Energy	Electronic throttle control and improved traffic flow should reduce energy consumed per kilometer traveled. These reductions may be offset by increased kilometers traveled.
Land Requirements	Land may be required at entrances/exits for check-in and check-out. Parking demands may increase. Possibly requirements for adding highway lanes.
Mobility	Increased capacity should reduce delay experienced per vehicle on the AHS1 facility and parallel arterials, though total delay across all vehicles may increase due to induced travel. Possibly increased congestion in vicinity of entrances and exits, though this can likely be mitigated.
Noise	Noise levels may increase due to increased traffic and speeds, though this may not be perceptible, especially if noise walls are provided.
Pricing/Equity	Means for recovering the cost of installing the AHS1 infrastructure is an issue, along with the question of restricted access to public facilities.
Safety	Uncertain risks. Collision warning may improve safety in some conditions, but operating in fully automated mode poses uncertain risks.

Table 11. Impacts and benefits of AHS2

User Impacts	Discussion
Energy	Reductions due to electronic throttle control, and reductions per kilometer due to reduced congestion on AHS1 and AHS2 equipped facilities.
Mobility	Improvements due to reduced congestion on AHS1 and AHS2 equipped facilities and on parallel arterials.
Performance	Electronic control may improve handling,braking,responsiveness. AICC, auto-steering and AHS1 and AHS2 provide enhanced comfort.
Safety	Safety warnings may improve safety. Uncertain hazards when operating in an automated mode.
System Impacts	
Air Quality	Electronic throttle control and improved traffic flow should reduce emissions per kilometer traveled. These reductions may be offset by increased kilometers traveled.
Capacity	Increase to 6,000 vehicles/hour on AHS2 facilities. No changes elsewhere.
Community	Possible impacts in immediate vicinity of AHS1 and AHS2 facilities, similar to that of conventional highwa ys.
Energy	Electronic throttle control and improved traffic flow should reduce energy consumed per kilometer traveled. These reductions may be offset by increased kilometers traveled.
Land Requirements	Land may be required at entrances/exits for check-in and check-out. Parking demands may increase. Possibly requirements for adding highway lanes.
Mobility	Increased capacity should reduce delay experienced per vehicle on the AHS1 and AHS2 facilities and parallel arterials, th e total delay across all vehicles might increase due to induced travel. Possibly increased congestion in vicinity of entrances and exits, though this can likely be mitigated.
Noise	Noise levels may increase due to increased traffic and speeds, though this may not be perceptible, especially if walls are provided.
Pricing/Equity	Means for recovering the cost of installing the AHS2 infrastructure is an issue, along with the question of restricted access to public facilities.
Safety	Uncertain risks. Collision warning may improve safety in some conditions, but operating in fully automated mode poses uncertain risks.

Furthermore, there are significant safety risks for configurations in which automated vehicles are mixed with conventional vehicles.

CHAPTER 5. COST EFFECTIVENESS OF CAPACITY INCREASES

The thrust of this chapter is on assessing the cost-effectiveness of using AHS to augment highway capacity within congested cities. This will be determined on a relative basis, compared to conventional means of adding capacity. The focus here is on AHS1 and AHS2, because they provide important system benefits. The benefits of ARV, on the other hand, are user focused. In addition, infrastructure investment appears to be minimal for ARV.

5.1 Differences Between AHS and Conventional Strategies

Prior to presenting analytical results, it is worthwhile to review some of the key differences between using AHS to augment highway capacity and using conventional strategies. This will help define some of the side benefits, or impacts, that may arise from automation.

5.1.1 Cost Differences: AHS Versus Conventional Highways

Vehicle Costs A unique aspect of AHS is that vehicles must possess specialized equipment to operate on an AHS1 or AHS2 facility. This implies that both vehicle and infrastructure costs affect system cost, and that the cost per unit capacity depends on the number of vehicles that must be equipped.

Recurrent Costs Unlike a conventional highway, which is somewhat self-operating, an AHS may require considerable recurrent expenditures for system operation and maintenance. Recurrent costs are also required for maintenance and replacement of vehicle equipment. Unfortunately, these costs remain largely uncertain.

Land Requirements By increasing the capacity per lane, or reducing lane width, AHS can reduce the space required to augment capacity. AHS may also, in some instances, preclude the need for expensive structures, which are sometimes used on space-constrained sites. AHS may also enable capacity to be augmented in locations where construction is otherwise impossible, as in narrow rights-of-way, such as abandoned rail lines.

Exclusive Facilities AHS may require some degree of separation from conventional traffic. Barriers between automated and conventional traffic, physical or otherwise, can add to construction cost.

5.1.2 Benefit Differences Versus Conventional Highways

Pollution Electronic throttle control has the potential for attaining improved engine performance, which may reduce emissions, whether operating on or off the AHS. The AHS may also enable somewhat smoother vehicle control, which can reduce pollution, though the benefit may be small relative to a conventional highway operating below capacity.

Energy As with pollution, electronic throttle control and smoother traffic may reduce energy consumption.

Safety In-vehicle sensors may reduce exposure to hazards, whether operating on or off the AHS. Under fully automated control, most current driver errors are eliminated, greatly reducing many categories of existing accidents. AHS may, however, create new safety risks, of yet unpredictable
magnitude.

Equity Because the AHS would likely only be accessible to equipped vehicles, categories of users would be excluded. However, if the added capacity is significant, non-AHS users would benefit from reduced congestion, whether operating on or off the AHS.

Comfort An AHS would likely provide substantial benefits in driver comfort, by relieving him or her of the driving task, and by providing smoother traffic flow.

5.1.3 Comparison to Alternative Modes

AHS might also be compared to non-highway options, such as rail transit, car-pools and buses.
Here, the comparison is much more complex, due to substantial differences in cost structures, travel time and comfort. Relevant issues include the following:

Costs Transit modes incur substantial operating costs due to high staffing requirements. However, they benefit from relatively small land requirements and, for buses, flexibility to augment capacity through use of existing roadways.

Travel Times Transit modes suffer from large access times, walking to/from stops and stations, and waiting for departures. While they benefit from circumventing congestion when separate guideways are used, this advantage is greatly reduced when compared to high-capacity AHS.

Parking Transit modes can either eliminate parking requirements, or move these requirements away from city centers, to suburban locations where land is more plentiful.

Pollution and Energy Transit modes generally reduce pollution and energy requirements, though the magnitude of these reductions varies greatly across locations, depending on passenger load sizes and vehicle types.

Safety Transit modes are on the whole safer than highway travel, largely due to larger vehicle size and greater control over operating conditions. Personal security can be an added risk with transit.

Equity Transit is in theory accessible to a greater portion of the population, because it is less restrictive with respect to disabilities, and does not require investment in vehicle purchases.

Comfort Like AHS, transit relieves the traveler from driving duties. However, transit riders sometimes are forced to stand or ride in crowded conditions. Unlike AHS, transit riders have less control over their surrounding environment, such as temperature, ventilation, music and noise.

5.2 Capacity Costs As a Function of Number of Equipped Vehicles

A critical dimension of AHS cost is the number of vehicles that must be AHS equipped in order to support the desired capacity. This number depends on a variety of factors, including the length and capacity of the AHS facility, trip length distributions, frequency of travel, distribution of trips over time, and demographics. These issues are discussed below.

Facility Length and Capacity Whether the facility is very short (under 1 km) or simply short (under 8 km), the number of equipped vehicles must be nearly the same. However, as the facility becomes longer, an increasing number of vehicles must be equipped to support the facility. Increases in capacity must also be supported by equipping more vehicles, in a somewhat proportionate fashion.

Trip Length Distributions Facilities that serve long trips require relatively fewer vehicles to be equipped than facilities that serve short trips, due to reductions in on/off traffic.

Frequency of Travel Commuters could make more effective use of equipment than occasional travelers, thus reducing the number of vehicles that must be equipped.

Distribution Over Time The AHS might only be used to supplement capacity during peak periods, in which case only commuters might need to be equipped. If AHS also serves base level demands, more vehicles would be equipped.

5.3 Cost Effectiveness Methodology

The cost effectiveness of the AHS is defined by the following ratio:

$$\frac{\text{[Annualized Infrastructure Cost per km]} + \text{[Annualized Fleet Cost per km]}}{\text{[Incremental Capacity]}} \qquad (1)$$

Hence, the effectiveness measure is the cost per unit capacity, per unit length of highway, per year. Cost is calculated on a bi-directional basis, and capacity is calculated on a one directional basis.

This equation is evaluated in the following steps:

(1) Determine fleet size, as a function of AHS capacity and AHS length.
(2) Annualize infrastructure cost, using annuity discounting equations.
(3) Annualize electronics cost per vehicle, using annuity discounting equations.
(4) Multiply annualized vehicle cost per vehicle by the fleet size to compute total vehicle cost per year.

(5) Substitute terms in Equation 1 to produce cost effectiveness measure.

The fleet size model is the most complicated. It is described in detail in the following section.

5.4 Vehicle Fleet Models

The goal of this section is to develop upper and lower bounds on the number of vehicles that must be equipped in order to support an AHS. These are defined by the following scenarios. Both scenarios assume constant traffic levels across the entire length of the AHS.

Lower Bound: Only commuters purchase AHS equipment, who use the AHS on a daily basis. The AHS is only used to meet peak period requirements, with the conventional highway serving base level demand.

Upper Bound: AHS capacity is used in both the peak and off-peak periods, in constant proportion. Equipped vehicles do not utilize the facility on a daily basis.

For both the upper bound and lower bound, the size of the vehicle population is estimated as a function of: facility length, facility capacity and average trip length. The distribution of traffic, by time of day, is based on a sample of five cities, taken from the ITE Handbook (24). Trips are assumed to originate and terminate at random over the length of the AHS, and all trips are assumed to be round-trip on the facility. Volume measures are based on screenlines and are assumed to be constant over the AHS length.

Lower Bound Calculation

Let:

- x = average trip length on highway (AHS and non-AHS)
- l = length of the AHS facility
- f' = maximum traffic volume supported in the corridor, one direction (conventional + AHS)
- f_t = traffic volume in corridor at time t (t = 1 to 24 hours), one direction
- F = total traffic volume per day in corridor, one direction
- a_t = traffic volume on the AHS at time t (t = 1 to 24 hours), one direction
- A = total traffic volume per day on AHS, one direction
- p = proportion of the maximum traffic volume that is served by the AHS
- r = frequency in which AHS equipped vehicles traverse the AHS facility (proportion of work days)
- n = number of AHS termini (a linear AHS is defined to have a single terminus, an X shaped AHS is defined to have two termini, and so on).

The r value translates traffic volume into number of vehicles. For instance, if r is close to one, then each unit of flow translates into one vehicle.

For the lower bound, we assume that $a_t = 0$ whenever f_t/f' is less than 1-p (i.e., the conventional highway accommodates base level traffic). The AHS accommodates the surplus. Then the traffic volume on the AHS is defined by the following, at any time t:

$$a_t = \begin{cases} 0, & f_t/f' < 1-p \\ f_t-(1-p)f', & \text{otherwise} \end{cases} \qquad (2)$$

The number of vehicles entering the AHS, per unit time, is somewhat larger than the traffic volume at any screenline, due to vehicles entering and exiting at intermediate points. The total equals the number of AHS termini, n, multiplied by the traffic volume, a_t, plus the number of vehicles that enter at intermediate points. This total, at any time t, is defined as e_t. Assuming, as stated earlier, that vehicles originate at random over the length of the AHS:

$$e_t = a_t[n + l/x] \qquad (3)$$

Finally, the total number of vehicles equipped for AHS must be the summation of e_t, divided by the frequency in which AHS vehicles traverse the highway (r). This total is defined as V:

$$V = \Sigma e_t/r = [n + l/x]/r \ \Sigma a_t$$
$$= A[n + l/x]/r ,$$
(4)

where:

$$A = \Sigma a_t \qquad (5)$$

The parameter A was estimated from data on hourly distributions of traffic volume, found in the ITE Handbook (24) , representing five United States Cities. Results are shown below, where A is presented as a ratio to F (total daily traffic volume):

p	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
A/F	.01	.03	.08	.15	.23	.32	.46	.63	.80	1.0

To take one example, these numbers indicate that if the AHS is intended to provide 50 percent of the peak period capacity, then 23 percent of the vehicles that traverse the highway must be AHS equipped. The relatively small number of equipped vehicles is due to the assumption that the AHS capacity is only needed to meet peak requirements, and not base level demand.

In calculations presented later, r is set to .9, which assumes that an average worker has about 26 days off per year. All trips are assume to be bi-directional. F is assumed to be a factor of 12.5 larger than the total corridors capacity, which is typical for congested U.S. highways.

Upper Bound Calculation

For the upper bound, the equation for a_t is modified by assuming that the AHS serves a constant proportion of traffic throughout the day:

$$a_t = pf_t \quad (6)$$

We assume no change in the expression for e_t and V. However, the value for r is reduced somewhat (to .5), because the AHS serves less frequent travelers. As with the lower bound, F is a factor of 12.5 larger than the capacity, and all trips are bi-directional.

Fleet Size Projections

Figures 2-5 give fleet size projections as a function of the length of the AHS (as a ratio to average trip length) and the percentage of the highway's capacity that is accommodated by the AHS (p=.2,.5,.8 and 1.0). Specifically, V/F is plotted as a function of l/x, for the cases n=1 and n=2, for both the upper bound and lower bound. These fleet sizes are the basis for the cost comparison that follows. Examining the figure, it appears that for an AHS of nominal length (l/x = 1, or AHS length equals average trip length, which is currently 10-15 miles) and capacity (p=.5), the lower bound estimate is that the fleet size equals about 50% of the daily traffic volume, or about 6.4 times the hourly capacity. The upper bound is that the fleet size is twice the daily volume, or about 25 times the hourly capacity. With a capacity of 4,000 vehicles per hour and l/x = 1, the fleet size is on the order of 25,000 to 100,000 vehicles, and with a capacity of 5,500 vehicles per hour, the fleet size is on the order of 34,000 to 140,000 vehicles.

5.5 Cost Effectiveness Calculation

Cost effectiveness estimates for AHS1 and AHS2 were based on the following assumptions:

- Only incremental vehicle cost is included. This is the difference between the cost for ARV and the cost for AHS1 or AHS2. (This reflects the assumption that user benefits justify ARV purchases).

- Capacity for AHS1 is 4,000 vehicles/hour per lane. Capacity for AHS2 is 5,500 vehicles/hour per lane, providing an incremental capacity of 3,500 (assuming the lane would otherwise carry 2,000 vehicles/hour). Only one lane is provided in each direction (multi-lane facilities would have lower capacity costs). Average freeway trip length is 16 km (a portion of which is on the AHS).

- Costs are based on year 2002 with 1,000,000 production.

- Infrastructure intensive electronics was assumed in both AHS1 and AHS2 due to lower costs.

- For AHS1, roadway option 5 was utilized, which provides a completely dedicated structure. This is the least expensive option for isolated lanes.

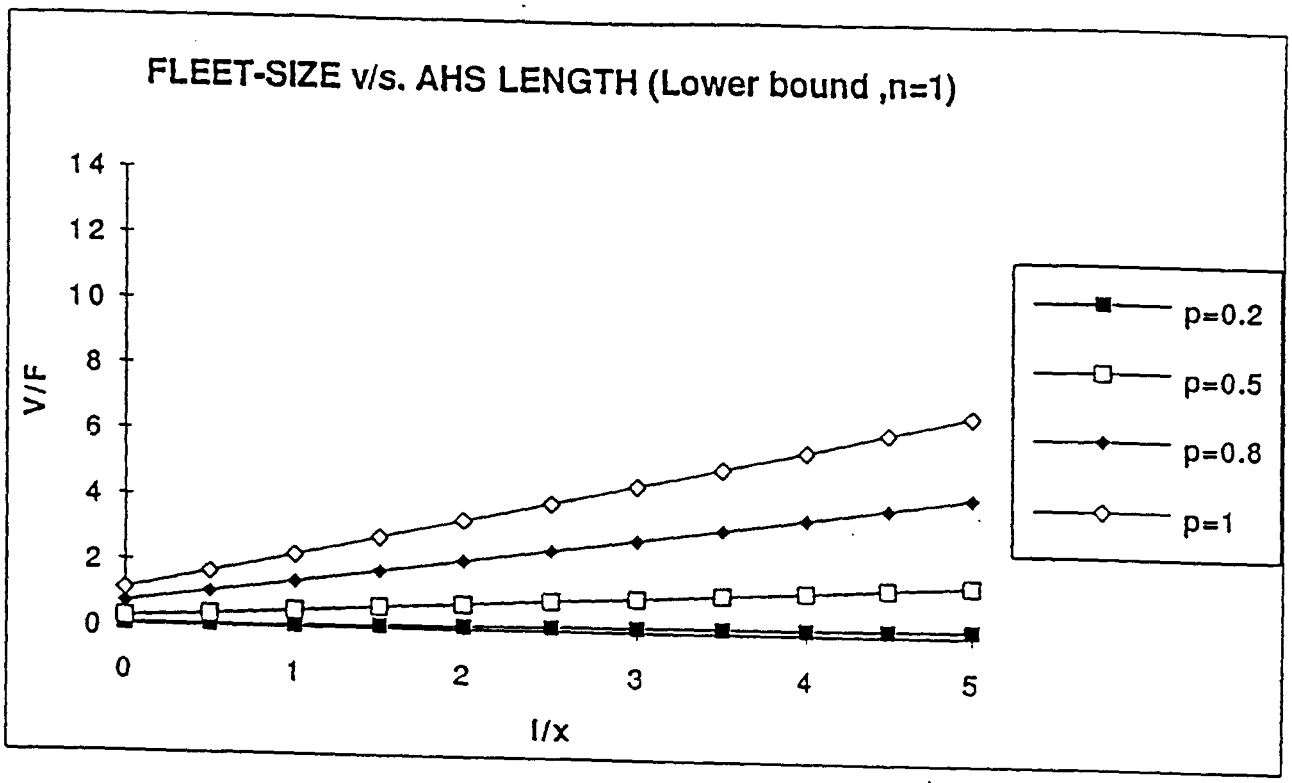

Figure 2. AHS fleet size projection: low estimate, n=1

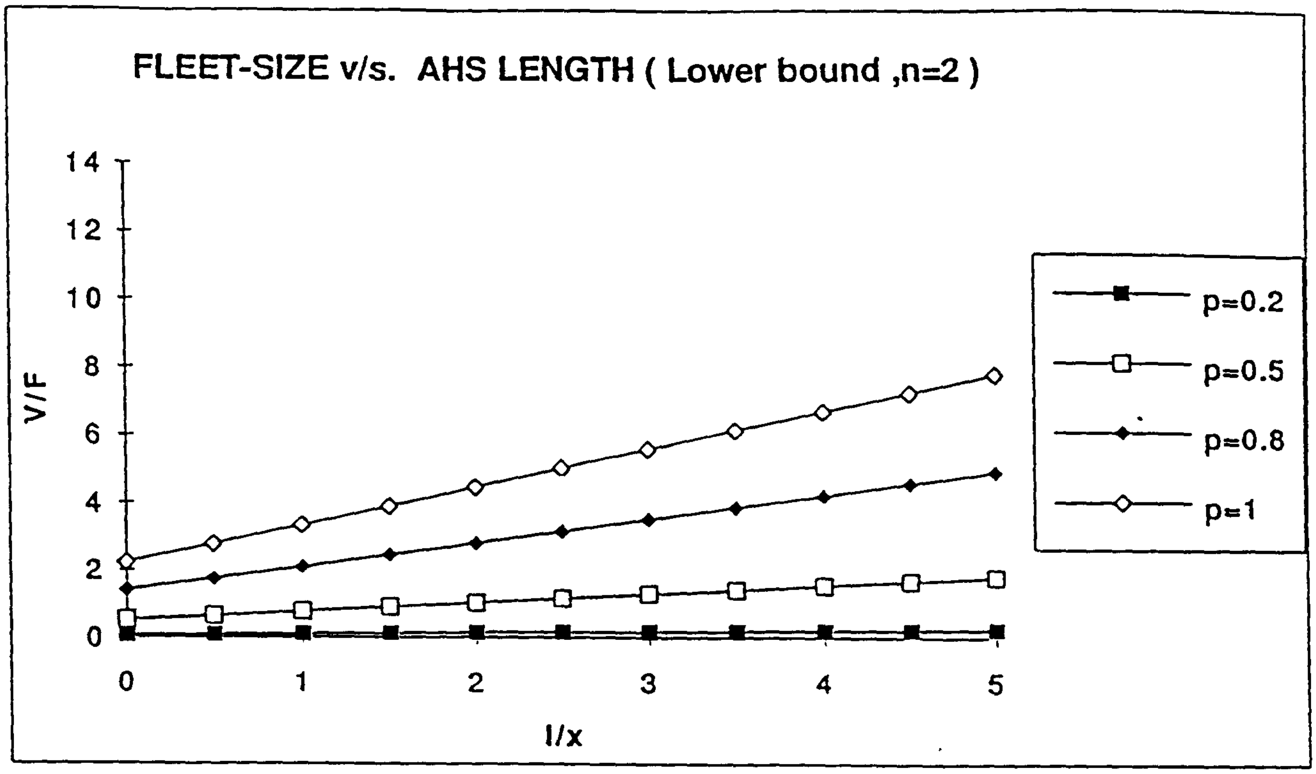

Figure 3. AHS fleet size projection: low estimate, n=2

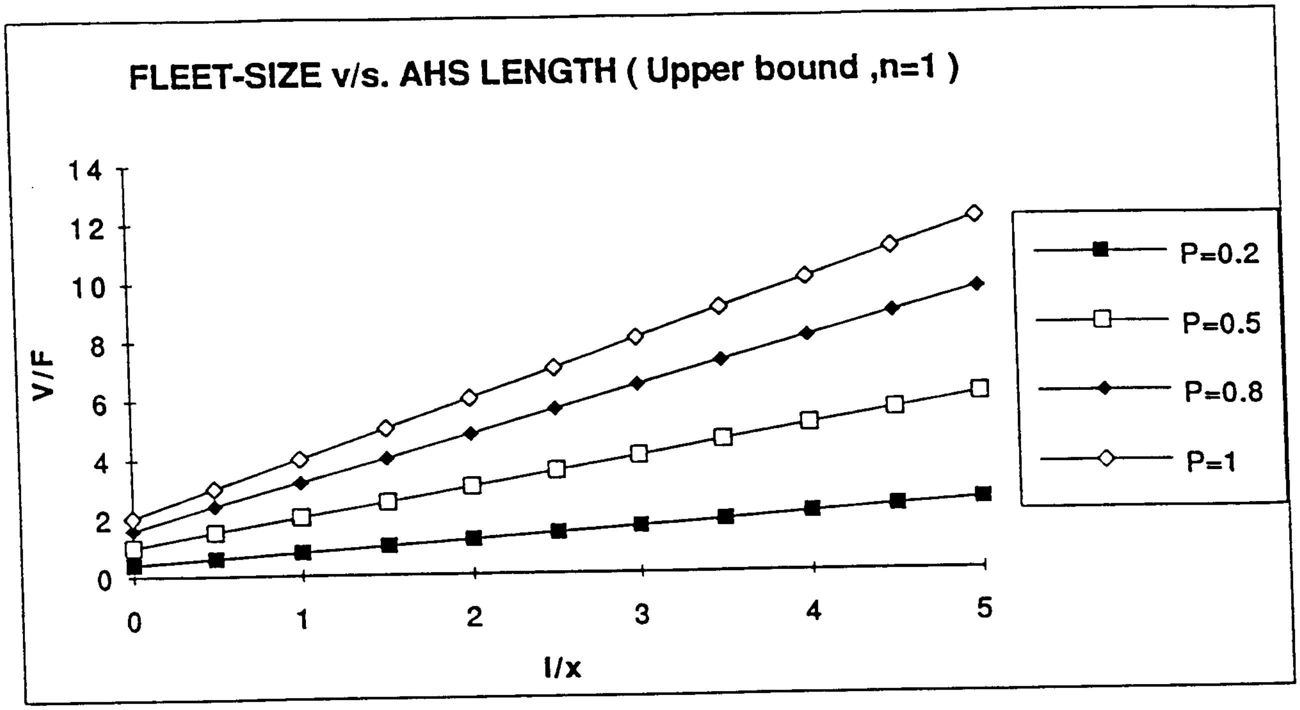

Figure 4. AHS fleet size projection: high estimate, n=1

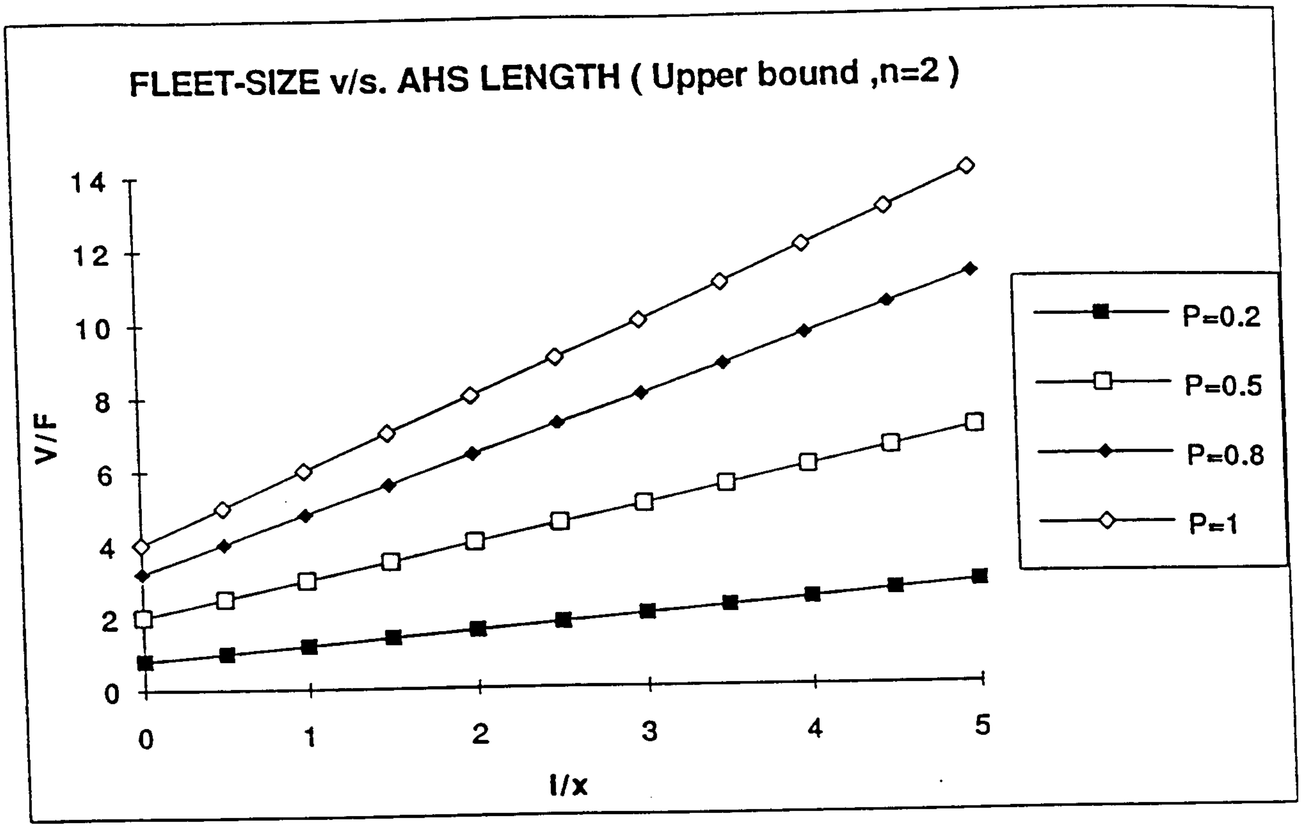

Figure 5. AHS fleet size projection: high estimate, n=2

- For AHS2, roadway option 4 was utilized, which does not require segregated lanes. This is the least expensive, and least risky, alternative that provided dedicated lanes with a transition.

- Vehicle lifetime is 10 years on average. Maintenance costs over this timespan is (10/7) of the 7 year lifespan estimate.

- Roadway electronics have a 20 year lifespan. Roadway construction has a 30 year lifespan. A 15% construction management fee is included.

- All cost analyses are in constant 1994 dollars. An after-inflation discount rate of 5 percent per year is used.

2002 is used to benchmark costs, even though AHS will not be implemented until a later date. 2002 was used because cost reductions are likely to reach a plateau, and the 2002 estimates seemed plausible.

High, medium and low estimates were created for AHS1 and AHS2, for facilities of varying length. The high estimates were based on the upper bound on fleet size, combined with the 95th percentile estimate for costs. The low estimates were based on the lower bound on fleet size, combined with the 5th percentile estimate for costs. Two medium estimates were produced, using the medium cost estimates, combined with the upper and lower bound on fleet sizes. All estimates may underestimate infrastructure electronics costs, as discussed earlier.

Cost results are provided in tables 12-13. Results are provided for AHS of lengths 3.2, 8, 16, 32, 64 and 128 km. For the two shorter lengths (3.2 and 8 km), the AHS is assumed to be linear (n=1); for the longer lengths, the AHS is assumed to have an X shape (n=2). Note that for AHS1, costs are fairly evenly divided between infrastructure and vehicles, while vehicle costs dominate for AHS2. Costs decline as the AHS length increases, because fewer vehicles need to be equiped per length of roadway. Also note that a wide range of uncertainty exists as to costs, due to the difficulties in predicting fleet size, and due to the underlying uncertainty in electronics costs.

Table 14 provides cost effectiveness measures, which are the annual costs per km of bi-directional roadway, as a ratio to the incremental capacity in each direction. The results come from the medium cost estimates, showing upper and lower bounds based on the fleet size model. Now it is clear that the AHS2 costs bracket the AHS1 costs, with AHS2 providing lower costs when smaller fleets are required. While AHS2 is attractive from the perspective of not requiring new infrastructure, it also takes capacity away from conventional roadways. Hence, more vehicles must be equipped to attain any incremental capacity addition, offsetting construction cost savings.

5.6 Comparison to Conventional Capacity Expansion

AHS is now compared to the least costly option for providing capacity by conventional means. For the U.S. 101 freeway, this entails building an elevated structure in the median.

The cost estimate is derived directly from the option 5 AHS roadway construction cost estimate. Of the

Table 12. Cost estimates for AHS1, option 5

ESTIMATES	Roadway construction & support costs ($/year/km.)	Vehicle purchase & support cost ($/year/km.) Length of roadway (km.) 3.2	8	16	32	64	128
High Estimate	$1,393,695	$13,173,059	$6,586,533	$6,607,627	$4,391,022	$3,292,988	$2,469,741
Medium Estimate (Upper Bound)	$1,337,480	$6,057,691	$3,028,842	$3,028,842	$2,019,229	$1,514,422	$1,135,816
Medium Estimate (Lower Bound)	$1,337,480	$1,017,258	$509,395	$509,395	$339,597	$212,248	$191,024
Low Estimate	$1,283,533	$467,578	$234,141	$234,141	$156,094	$97,556	$87,802

Table 13. Cost estimates for AHS2, option 4

Roadway construction & support costs ($/year/km.)	Vehicle purchase & support cost ($/year/km.)					
	Length of roadway (km.)					
$33,784	3.2	8	16	32	64	128
High Estimate	$20,066,658	$10,033,290	$10,033,290	$6,688,860	$5,016,645	$4,180,538
Medium Estimate (Upper Bound)	$8,823,893	$4,411,946	$4,411,946	$2,941,298	$2,206,749	$1,838,958
Medium Estimate (Lower Bound)	$2,144,696	$1,072,359	$1,072,348	$714,575	$536,363	$446,330
Low Estimate	$928,391	$464,200	$464,195	$309,324	$232,098	$193,138

Table 14. Cost Effectiveness of highway automation (medium estimates)

Vehicle purchase and support cost (S/year/km/capacity)

	Length of Roadway (km)					
Scenario	**3.2**	**8**	**16**	**32**	**64**	**128**
AHS1 (upper bound)	1849	$1092	$1092	$839	$518	$450
AHS1 (lower bound)	$589	$461	$461	$419	$282	$278
AHS2 (upper bound)	$2530	$1270	$1270	$850	$640	$534
AHS2 (lower bound)	$622	$316	$316	$214	$163	$137

total cost $278,610,000, all but $276,390,000 would apply to a conventional structure. This was converted into an annual cost, assuming a 30 year lifetime, and a 5% after inflation discount rate, resulting in the following cost estimate (also including 15% for constuction management):

Conventional Cost Estimate: $1,286,000 /km per year

With an estimated capacity of 2,000 vehicles/hour per direction, this amounts to the following cost-effectiveness estimate:

1 lane/direction
Conventional Cost Effectiveness: $643/km per year, per unit of hourly capacity

The cost effectiveness for a multi-lane structure would be somewhat better. Construction cost would increase by approximately 60% (assuming structure cost is proportional to structure width) while capacity would double, resulting in the following cost effectiveness:

2 lanes/direction
Conventional Cost Effectiveness: $514/km per year, per unit of hourly capacity.

These numbers are comparable to the AHS estimates, except for longer systems. Because of the considerable uncertainty in AHS costs, it is highly uncertain whether AHS offers cost savings relative to conventional highway expansion.

Nevertheless, if equipment is purchased primarilly by frequent commuters, who travel during peak periods, the savings can be substantial (perhaps 50% or more). Taking 64 km as a benchmark system, and averaging the upper and lower bounds, the savings would amount to approximately $110/km per year, per unit of hourly capacity (a 20% cost reduction).

Clearly, the cost effectiveness of AHS hinges on construction cost savings. Based on this limited case study, it appears that the biggest savings come from eliminating lane construction completely, as might be possible under AHS2, combined with establishing relatively small fleets, focused on peak period commuters. It would also be necessary to establish fairly large systems, to enable greater utilization of AHS equipped vehicles.

It should be borne in mind that for locations having low construction costs (e.g., where right-of-ways are large), AHS will be less attractive. On the other hand, the cost effectiveness measures do not reflect secondary AHS benefits, which might come from safety improvements, pollution reductions, etc.

CHAPTER 6. COST/BENEFIT SYNTHESIS

The purpose of this chapter is to extrapolate the results from a single facility to the nation as a whole. An important consideration here is whether there is a sufficient national market to justify manufacturer investments in producing and selling AHS equipment.

6.1 Market Penetration Rates and Vehicle Sales

As mentioned earlier, the AHS Ready Vehicle is a precursor to the construction of high-capacity AHS. This section investigates the length of time required before the population of ARVs is sufficient to justify AHS construction. Results are based on the annual turnover of the vehicle fleet, and possible market penetration rates, taken from existing technologies. Conventional cruise control, ABS braking, and air bags are used for comparison purposes. The analysis was performed in three steps:

(1) Forecast total vehicle sales by year.
(2) Forecast market penetration by year for ARV, to compute ARV sales.
(3) Forecast retirement rates by year, to compute ARV fleet size.

Automotive News [25] was used as a data source in all three steps.

Total Sales The forecast used a non-linear regression model, based on total sales of domestic and import automobiles and small trucks, using 1966 to 1989 as a basis.

Market Penetration High, medium and low estimates were produced, based on historical data for driver side air bags (high), ABS braking (medium), and cruise control (low). For each case, a Gompertz type (double exponential) technology diffusion model was used to represent market penetration as a function of years since introduction, based on a least-square model fit to historical data.

Retirement Rates This represents the rate at which vehicles are taken out of operation. The total fleet size in any year is the fleet size from the previous year, plus the new sales, minus retirements (net import/export of used vehicles is viewed as insignificant). These values were computed by averaging the retirement rates over 14 years for cars sold in 1966 through 1989 as of 1990.

Figures 6 and 7 provide vehicle sales estimates by year, assuming that ARV technology is introduced in the year 2000. As shown, based on historical comparisons, it will optimistically take 3 to 10 years *from introduction* before ARVs constitute 20 percent of sales, and 5 to 18 years before ARVs constitute 50 percent of sales. It will take considerably longer before ARVs reach these percentages in the total fleet. As shown in figures 8 and 9, it will take 6 to 14 years from introduction before ARVs constitute 20 percent of the fleet and at least 10 years, and likely 14 or more, before ARVs constitute 50 percent of the fleet. It should be borne in mind that the optimistic estimates are based on the experience with driver-side airbags, whose market growth was stimulated by safety regulations. Hence, it would be quite unrealistic to expect faster market penetration.

It should be borne in mind that the fleet size for AHS1 and AHS2 may be considerably smaller than the fleet size for ARV. Only a fraction of the vehicles need to upgrade in order to fully utilize the AHS facilities. It is unclear, however, how big the pool of ARVs must be in order to generate a sufficient number of AHS1 or AHS2 equipped vehicles.

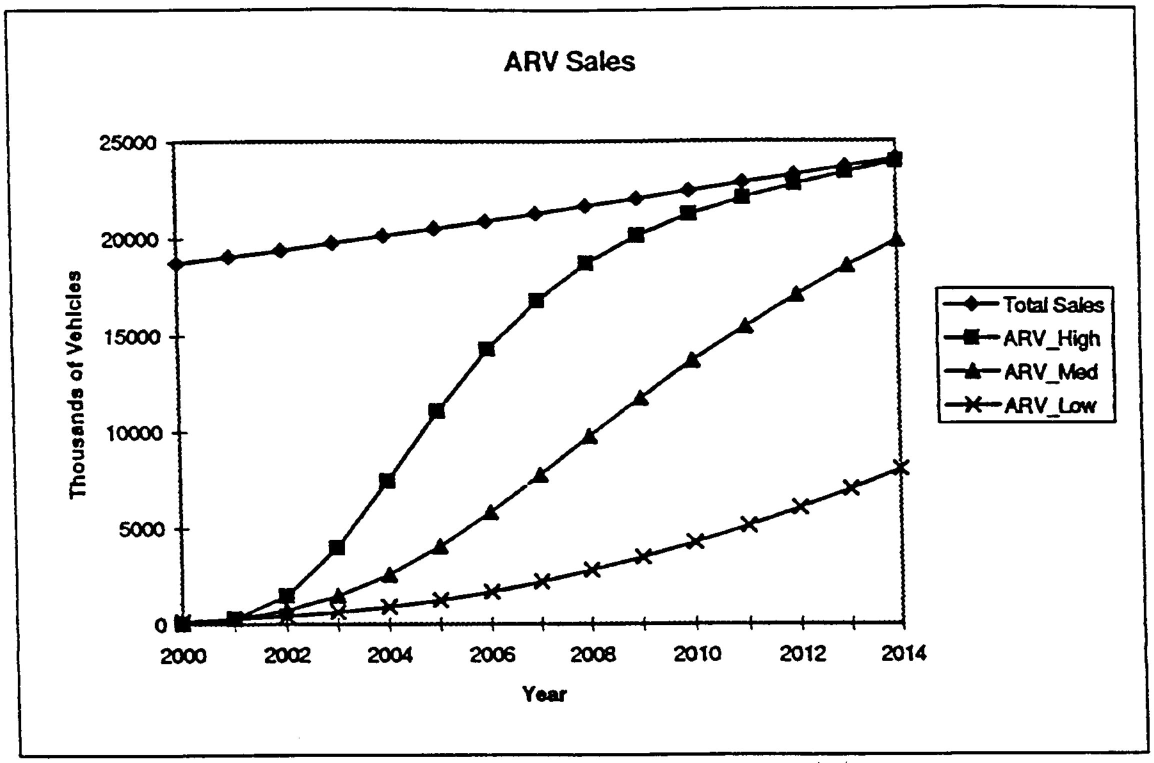

Figure 6. ARV sales projections by year

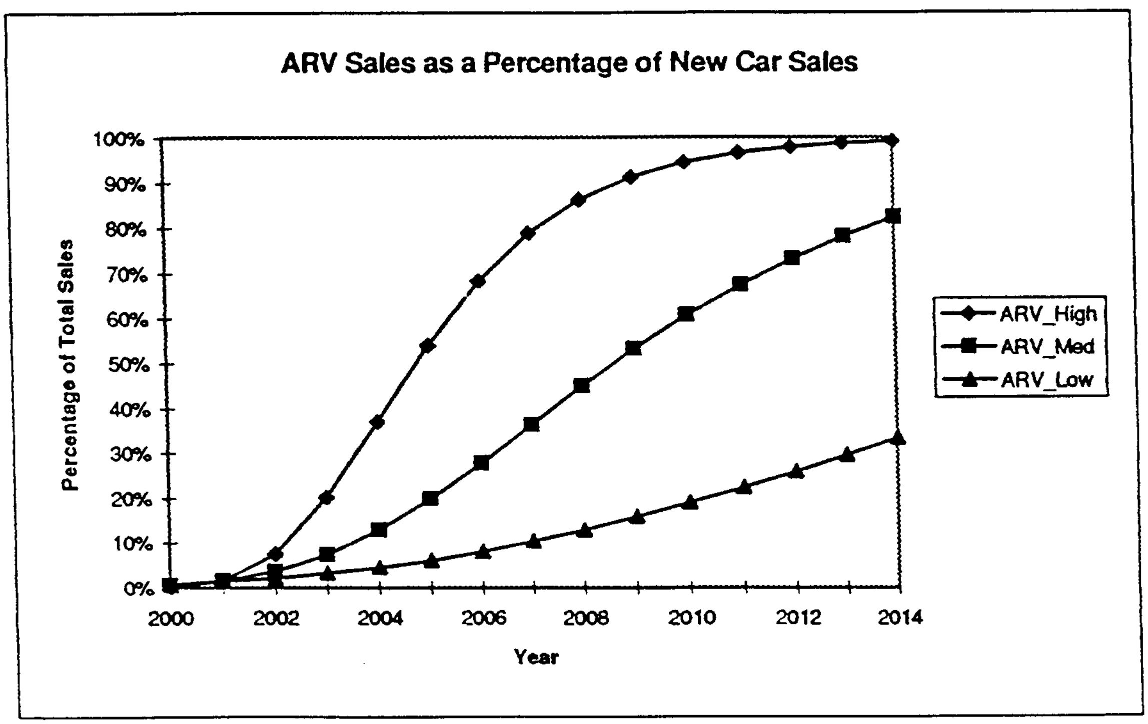

Figure 7. ARV sales as a percentage of total new car sales by year

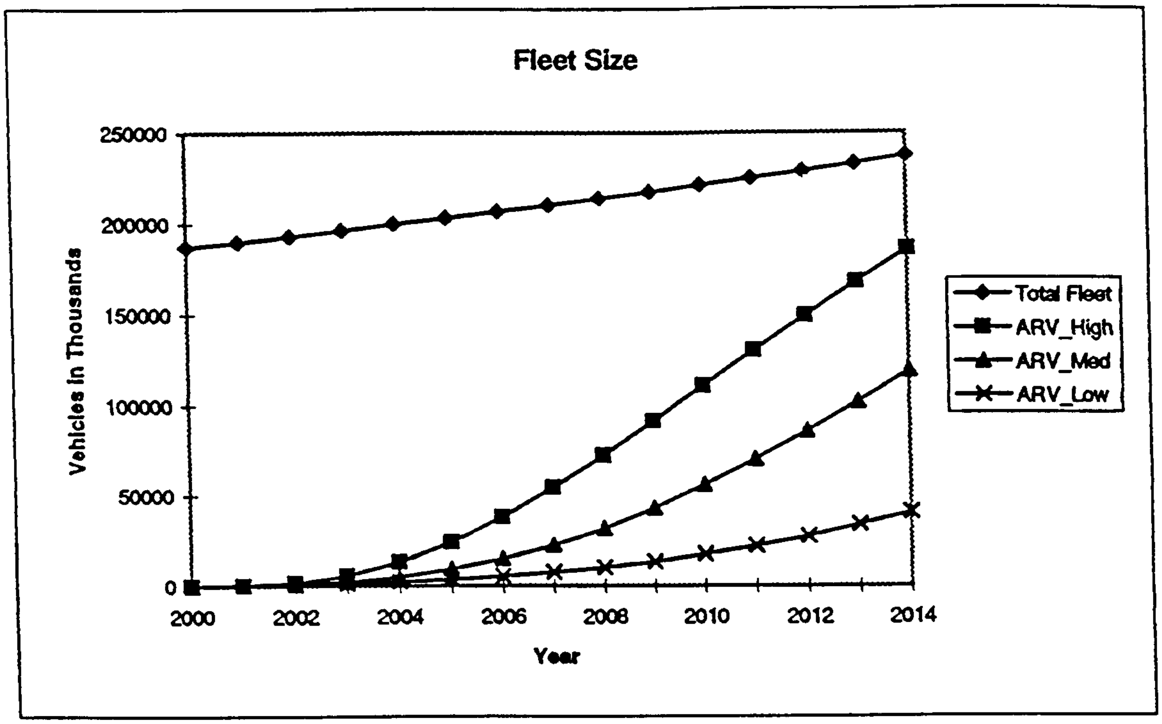

Figure 8. ARV fleet size by year

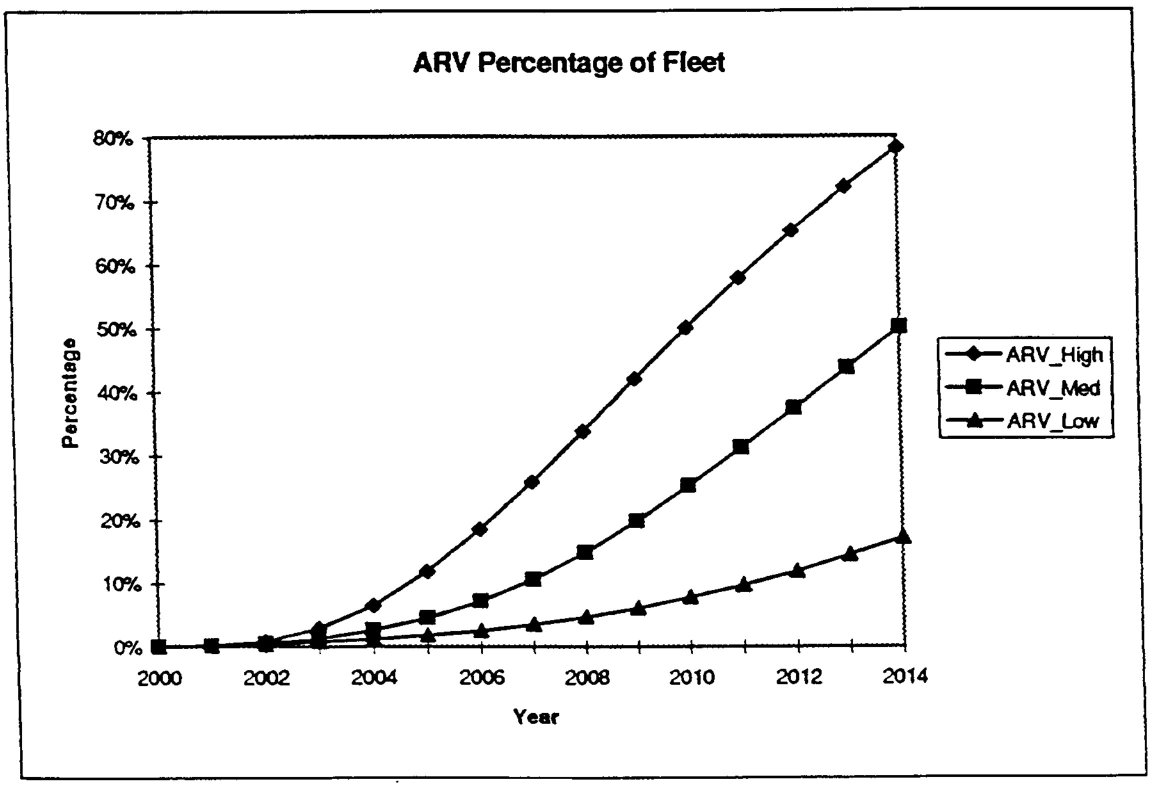

Figure 9. ARV fleet size as a percentage of total fleet size by year

6.2 AHS Potential in United States Cities

Transportation conditions vary considerably across (and within) United States cities. Whereas some cities have relatively large freeway networks relative to their population (e.g., Kansas City), others do not (e.g., Phoenix). Whereas some cities have significant congestion problems (e.g., Los Angeles), others do not (e.g., Salt Lake City). Whereas some cities have high land costs (e.g., San Francisco), others do not (e.g, Dallas). Whereas some cities are growing rapidly (e.g., Sacramento), others are shrinking (e.g., Pittsburgh). And whereas some cities have high personal incomes (e.g., New York), others do not (e.g., San Antonio).

All of these factors contribute to the desirability of constructing AHS facilities relative to employing conventional strategies. At the risk of oversimplification, an ideal candidate city for AHS would have the following characteristics:

- Significant Congestion
- Small Existing Transportation Infrastructure
- High Land Costs
- Rapid Growth
- High Personal Income (so that people can afford vehicle equipment)

Taking these considerations into account, a procedure was developed for estimating the potential for AHS construction by the year 2020 in 29 of the nation's largest cities. The procedure is inexact, but is easily refined through further study. The steps follow :

(1) Rate each city on a scale from 0 to 1 according to three criteria: (a) hours of congestion per automobile commuter [26], (b) average price of a comparable home [27], and (c) per capita income [28]. Home prices are used as a proxy for land prices, which were not available. A rating of 1 is assigned to the city that rates highest for a given criterion, a rating of 0 is assigned to the city that rates the lowest, and ratings for other cities are interpolated between the extremes. These scores are then summed across the three criteria to produce an overall score, and an overall ranking of cities according to desirability of AHS construction (table 15).

(2) Produce high, medium and low estimates for construction of AHS lane-kilometers between the years 2000 and 2020, based on the following:

a) For all estimates, assume population grows at the same rate as the 1980-1990 period

b) For low estimate, the ratio of freeway capacity to the number of auto commuters stays the same as 1990.

c) For medium estimate, for cities with a lower than average number of freeway lane kilometers per auto commuter, the ratio of capacity per auto commuter increases to the

Table 15. Scoring of major United States cities for AHS desirability

		SCORES			
No.	*Metropolitan Area*	*Land Prices*	*Delay*	*Income*	*Total*
4	San Francisco	1.00	0.76	0.98	2.74
8	Baltimore/Washington	0.58	1.00	0.83	2.40
1	New York City	0.56	0.47	1.00	2.03
2	Los Angeles	0.90	0.57	0.50	1.97
7	Boston	0.62	0.47	0.78	1.87
5	Philadelphia	0.66	0.20	0.64	1.50
15	San Diego	0.81	0.23	0.41	1.45
14	Seattle	0.23	0.58	0.57	1.38
9	Dallas/Fort Worth	0.17	0.73	0.45	1.35
3	Chicago	0.35	0.25	0.66	1.26
21	Denver	0.33	0.26	0.55	1.14
11	Miami	0.17	0.43	0.43	1.02
12	Atlanta	0.10	0.41	0.46	0.97
25	Sacramento	0.30	0.26	0.38	0.95
16	Minneapolis	0.20	0.13	0.60	0.93
6	Detroit	0.15	0.28	0.47	0.90
10	Houston	0.00	0.46	0.43	0.90
17	St. Louis	0.05	0.20	0.48	0.73
23	Milwaukee	0.16	0.09	0.45	0.70
19	Phoenix	0.10	0.34	0.25	0.68
18	Pittsburgh	0.10	0.19	0.39	0.67
26	Portland	0.14	0.22	0.31	0.67
22	Cincinnati	0.24	0.04	0.33	0.60
13	Cleveland	0.06	0.04	0.39	0.49
20	Tampa	0.04	0.16	0.28	0.48
28	Indianapolis	0.06	0.00	0.42	0.48
24	Kansas City	0.01	0.00	0.43	0.43
27	San Antonio	0.03	0.13	0.03	0.18
29	Salt Lake City	0.09	0.00	0.00	0.09

Table 16. Estimated AHS2 lane-kilometers constructed by 2020

	CITY'S REQUIREMENT (km)			CUMULATIVE REQUIREMENT		
Metropolitan Area	*Minimal*	*Middle*	*Maximum*	*Minimum*	*Medium*	*Maximum*
San Francisco	483	858	2481	483	858	2481
Baltimore/Washington	547	707	2413	1030	1565	4893
New York City	199	1590	5074	1228	3156	9967
Los Angeles	1707	2733	6837	2935	5889	16804
Boston	89	708	1869	3024	6597	18673
Philadelphia	64	865	2090	3088	7463	20762
San Diego	769	1793	3815	3856	9256	24577
Seattle	331	489	1339	4187	9746	25916
Dallas/Fort Worth	1167	6041	11607	5354	15787	37523
Chicago	43	255	1413	5397	16042	38936
Denver	148	1829	3528	5544	17871	42464
Miami	150	479	1072	5695	18350	43536
Atlanta	710	710	1077	6405	19060	44614
Sacramento	314	314	565	6719	19374	45178
Minneapolis	237	330	1101	6956	19704	46279
Detroit	0	2477	4987	6956	22181	51266
Houston	415	590	1728	7372	22771	52994
St. Louis	48	52	704	7419	22823	53698
Milwaukee	16	220	626	7435	23043	54325
Phoenix	171	307	662	7607	23350	54986
Pittsburgh	0	0	165	7607	23350	55151
Portland	94	174	533	7701	23524	55685
Cincinnati	52	331	939	7753	23855	56624
Cleveland	0	16	440	7753	23871	57064
Tampa	105	105	252	7858	23976	57316
Indianapolis	61	61	410	7919	24037	57727
Kansas City	161	453	1391	8080	24490	59118
San Antonio	226	226	494	8305	24716	59611
Salt Lake City	93	93	93	8398	24809	59704

current average. For cities with a higher than average ratio, the current ratio is maintained (resulting in an average capacity increase of roughly 26 percent, population adjusted)

d) For high estimate, assume that the ratio increases to the current maximum (using Kansas City as a benchmark) in all cities (resulting in an average capacity increase of roughly 147 percent, population adjusted).

(3) Combine the results of (1) and (2), to estimate the required AHS lane kilometers (counting both travel directions). This is performed as a parametric analysis, based on the rank ordering of cities from step (1). Adjust requirement to account for higher capacity of AHS lanes (on a ratio of 2.75 to one, assuming 100 percent AHS2 at that time). Results are in table 16.

Figure 10 is the result of steps 1-3. This graph indicates that the high estimate for AHS lanes is on the order of 60,000 supplemental kilometers (30,000 in each direction), based on an aggressive program of building AHS only in the 29 cities, and greatly increasing available highway. A much more realistic estimate would come from a medium level of construction in those cities that rate above 1.5 in overall score (this represents the midpoint of the ranges for the three criteria combined). These cities are: San Francisco, Baltimore/Washington, New York City, Los Angeles, Boston and Philadelphia.

Total construction would amount to approximately 7,500 supplemental lane kilometers (3,750 in each direction), providing a population adjusted capacity increase of 18% within the six high priority cities. These numbers assume that only AHS is used in these cities, and that no AHS is used elsewhere. In reality, some mixture of AHS and conventional capacity will likely be used, though the total lane-kilometers across the country may be of comparable value. All estimates assume that no conventional capacity is removed. If conventional capacity is removed, then AHS construction would have to be larger.

It should be noted that a number of cities rate low relative to all three criteria for AHS desirability, such as Salt Lake City, San Antonio, Kansas City and Indianapolis. It may well be that AHS is not the solution for all places. These rankings provide a preliminary indication of where AHS is most likely to be viable.

6.3 Market Penetration Potential for AHS Vehicles

This section uses the 7,500 kilometers (3,750 per direction) of added AHS capacity by 2020 as a benchmark, and extrapolates to estimate the number of vehicles that must be AHS equipped. It should be recognized that while 7,500 km of construction is a large number, it is still a small percentage of the nation's total freeway system. The capacity amounts to roughly 30% of the existing capacity in the 29 cities studied (covering a little less than half of the U.S. population). Hence, only a fraction of the fleet must be AHS equipped in order to fully utilize the system.

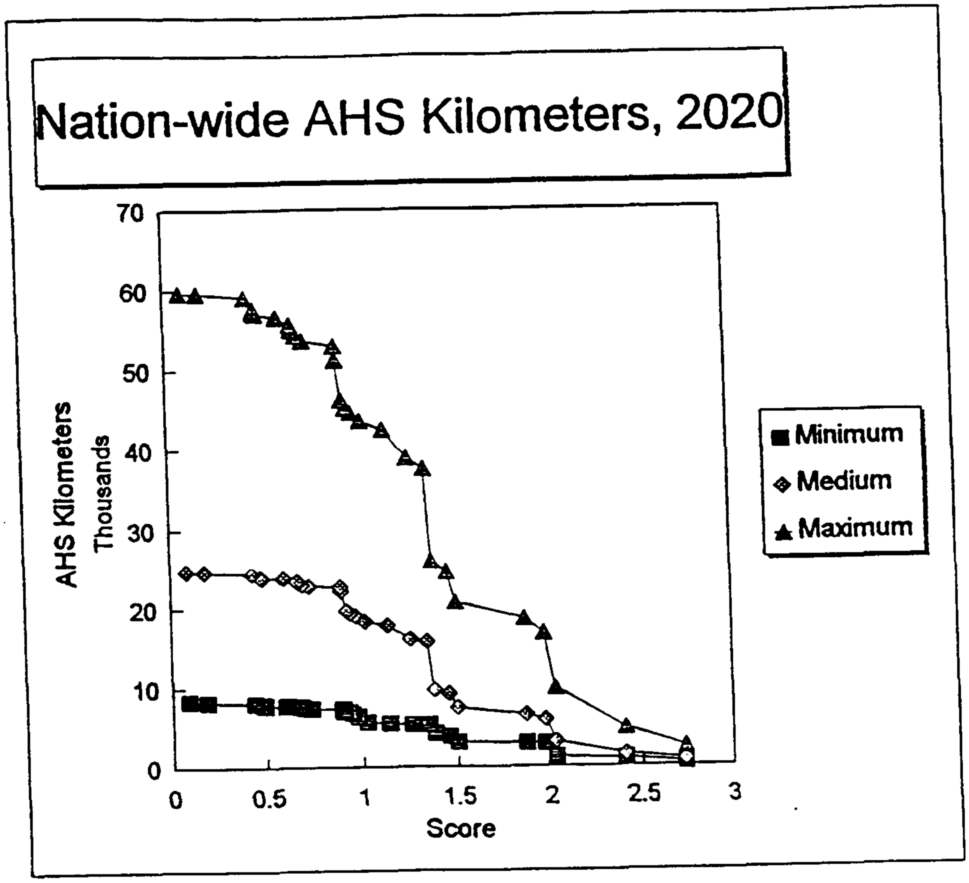

Figure 10. Estimated nation-wide lane-kilometers of AHS for year 2020

Chapter 5 provides a model that converts freeway lane-km into fleet size, providing high, and low estimates. Modifying this model slightly, and assuming average trip lengths of 16 km, the estimated size of the AHS fleet in 2020 is on the order of 13 to 20 million vehicles, which is on the order of 5% of the total fleet for 2020. This is less than the projected fleet size for ARVs, for which the medium estimate is 50% of total fleet.

It should again be pointed out that the ARV may be essential to the eventual adoption of AHS1 and AHS2. Because AHS infrastructure is only reasonably required in a limited number of locations, there might not be sufficient market size to justify manufacture of AHS vehicles without the simultaneous manufacture of ARVs. While a 5% fleet penetration is likely sufficient to gain scale economies in component production, it is not sufficient for scale economies in vehicle manufacture. It would be unreasonable, for instance, to produce two versions of a vehicle, one with electronic steering, braking and propulsion, and another without. In order for AHS to be successful, a likely requirement is that all vehicles produced of certain models contain ARV features. These would be sold throughout the United States. Components allowing upgrade to AHS1 and AHS2 would then be customer options, available only in the regions where AHS1 and AHS2 infrastructure is constructed.

6.4 Nationwide Cost Savings

Nationwide, the potential cost savings from applying AHS technology in place of conventional roadways is calculated as follows:

Nationwide Savings/Year = Kilometers Constructed *(Cost Difference/kilometer-year)

As estimated in Chapter 5, the cost savings per kilometer/year is estimated to be on the order of $110/yr per km, per unit of capacity (based on AHS2). Using 3,750 as the estimated number of lane-kilometers constructed (bi-directional), total cost savings amount to $2.3 billion/year, in current dollars. As a point of comparison, this would amount to an inflation adjusted 5 percent return on a $11 billion investment, deferred by 25 years (investment made in 1995, with benefits accruing in 2020 and later).

As stated previously, this cost result does not take the following factors into account:

- Costs and benefits associated with the ARV vehicle (e.g., only incremental cost above ARV cost is included).
- Benefits, other than capacity, associated with AHS.

The estimates do assume, however, that there will be a large population of ARV vehicles prior to the construction of AHS infrastructure, both to reduce the cost per vehicle and to make early deployments viable. Also, it should be borne in mind that there is considerable uncertainty as to electronics costs, especially in the infrastructure. It is quite possible that AHS could turn out to be prohibitively expensive. On the other hand, there is also a strong potential for AHS2 to be a cost effective strategy for solving congestion problems.

CHAPTER 7. CONCLUSIONS

The key conclusions of the study follow:

- An evolutionary deployment strategy provides: interim benefits, refinement of technologies in less demanding situations, build up of a vehicle fleet prior to expensive construction, and scale economies in manufacture. The evolutionary stages are defined as ARV (AHS Ready Vehicle), AHS1 (high capacity, with manual lane change) and AHS2 (highest capacity, with automated lane change).

- For the year 2002, with 1,000,000 vehicles in production, the 7 year life cycle costs are as follows: $2,068 for ARV, $3,412 for AHS1 and $3,498 for AHS2 (all measured in 1994 dollars, assuming infrastructure intensive systems). The range of uncertainty in these estimates is roughly -70% to +50%.

- For the case study highway (U.S. 101 in Los Angeles), the least expensive method for adding lanes is to provide an elevated structure with dedicated on/off ramps. The cost amounts to $17.5 million/km, with one lane in each direction (1994 dollars). The range of uncertainty in this estimate is small.

- The cost of converting lanes to AHS is far less than the cost of constructing entirely new lanes -- on the order of $300,000/km with one lane in each direction (1994 dollars).

- Numerous prior studies have examined AHS impacts, with respect to air quality, capacity, energy, safety, mobility and other factors. Estimates in these studies have considerable uncertainties for two reasons: (1) the actual performance of an AHS is not yet known, and (2) the reaction of consumers and travelers to AHS technology is unknown.

- The cost effectiveness of AHS depends on the cost for constructing the infrastructure and the cost of equipping the fleet. For AHS1, these costs are of similar magnitude. For AHS2, where lane conversion is employed, vehicle costs dominate.

- For the case study highway, the cost per unit capacity is somewhat lower for AHS1 and AHS2 than conventional highway expansion. The cost is potentially 20 percent less for AHS2, factoring in savings in roadway construction cost.

- Based on historical market penetrations for cruise control, ABS braking and driver-side air bags, ARVs are unlikely to reach a fleet penetration of 20% before 2009 and unlikely to reach a fleet penetration of 50% before 2014. This is based on 2000 as the year of introduction.

- For the year 2020, high capacity AHS appears to be most viable in the cities of San Francisco, Washington/Baltimore, New York, Los Angeles, Boston and Philadelphia. Total AHS lane kilometers in these cities could reasonably amount to 3,750 per direction, representing an effective 18% increase in capacity in these cities (population adjusted).

- Using 3,750 lane km as a benchmark, the total number of vehicles equipped for AHS1 or AHS2 in 2020 is on the order of 13-20 million vehicles, roughly 5% of the fleet.

- It would be difficult to attain scale economies in AHS1 or AHS2 without the simultaneous sale of ARVs. ARVs could reasonably be marketed nationwide, while AHS1 and AHS2 equipment could be customer options, available in those cities where high capacity AHS roadways are constructed.

- Annual cost savings, based on 3,750 km in service, amount to $2.3 billion per year for AHS2, assuming new lanes do not have to be constructed. This represents a 5% annual return on a $11 billion investment, deferred 25 years. For both AHS1 and AHS2, cost estimates contain considerable uncertainties.

Final Comments

All conclusions are qualified. Due to the preliminary nature of the PSA program, the report is intended more to demonstrate a methodology than to provide definitive answers. This methodology can be refined through activities of the AHS consortium. Areas where further work is especially needed include the following:

- Estimation of infrastructure electronics costs, both in installation and operation.

- Analysis of fault tolerance, the need for redundant systems, and the need for environmental sensors, along with associated costs.

- Market penetration estimates, and determination of the relationship between infrastructure construction and vehicle sales.

- Review of specific needs of U.S. cities for highway construction, and assessment of AHS in meeting these needs.

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Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Cost/Benefit Analysis

Volume II: System Configurations: Evolutionary Deployment Considerations

U.S. Department of Transportation
Federal Highway Administration

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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

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ABSTRACT

This Volume presents and justifies the Representative System Configurations used to perform the Cost/Benefit Analysis task. These configurations are based on the philosophy that AHS technologies will evolve over time as a result of technology advancements, changes in market penetration, and changes in roadway construction. At any point in time, there will be a mixture of vehicle types, with varying capabilities, and a mixture of roadway types.

The configurations utilize the "AHS Ready Vehicle" (ARV) as a stimulus for initial sales, and eventual adoption of fully automated vehicles. The ARV is capable of hands-off and feet-off driving under low volume conditions, as on many inter-city highways. The motivating factors for purchase are primarily comfort and performance. Later on, an ARV might be upgraded to allow for operation on high-volume roadways, where the added benefit is reduced travel time due to avoidance of congestion. Later stages of evolution are defined as AHS1 (fully automated, high-volume, with manual lane changes) and AHS2 (fully automated, high-volume, with automated lane changes).

For each stage of evolution, various implementation strategies are presented. For electronics, these strategies are defined as "minimum infrastructure modification" versus "infrastructure intensive", and by "dedicated lanes" versus "mixed traffic." Taking various combinations into account, a total of seven electronics configurations are defined. For roadways, five strategies are defined, defined by whether dedicated or mixed lanes are provided, and access to automated lanes.

The implementation strategies are the basis for the cost/benefit analysis presented in Volume 1 of the AHS Cost/Benefit task, and for the cost analyses presented in Volumes 3 and 4.

ACKNOWLEDGMENTS

The electronics scenario contained in this report is based on the contributions of Rockwell International (details can be found in Volume III). The roadway scenario is based on the contributions of Bechtel (details can be found in Volume IV).

CHAPTER 1. BACKGROUND

The goal of the Precursor System Analysis (PSA) Cost/Benefit task is to develop a framework for the evaluation of alternative Automated Highway System (AHS) concepts, with respect to full life-cycle costs and benefits. This framework will be applied to a range of scenarios, to capture benefits and costs on a regional and national basis. The framework will account for risks and uncertainties, with respect to such factors as market penetration, construction and vehicle costs, and public acceptance of new facilities. In addition to producing the evaluation framework, this activity will help identify the types of locations that would benefit most from AHS, as well as strategies for evolutionary deployment.

The purpose of this report is to document the evolutionary deployment strategies used in the research. These strategies focus on technologies which are essential to automated highway systems and, as a consequence, should be included in AHS cost and benefit estimates. While technologies for advanced traveler information and advanced traffic management are related to highway automation, they are not essential. Therefore, they will not be covered in the evolutionary deployment strategy presented here.

The overall philosophy is to develop a plausible scenario for AHS development that is responsive to market forces and does not stretch technological limits in early stages of deployment. In developing this scenario, many uncertainties exist. Hence, this document represents only one of many possible plans.

The remainder of this report is divided into six sections. First, publications on evolutionary deployment is reviewed. Next, criteria are created for development of evolutionary strategies, and the dimensions of evolution are defined. Then the evolutionary strategy to be used in the cost/benefit task is introduced, first at a functional level, and then in terms of specific technologies. Finally, the next steps of the research are provided.

CHAPTER 2. RELATED PUBLICATIONS

The IVHS America Strategic Plan (1) provides a set of milestones covering all of IVHS, including Advanced Traffic Management Systems, Advanced Traveler Information Systems, Advanced Vehicle Control Systems, Commercial Vehicle Operations and Advanced Public Transportation Systems (Table 1). For each of these areas, the Strategic Plan discusses the state-of-the-art and ongoing research as well as operational testing and future plans. In addition, the document presents a vision for how research, development and implementation of IVHS capabilities should evolve over the next 20 years. The plan also discusses societal and legal concerns including product liability and other tort liability, antitrust, privacy, procurement, intellectual property and regulation, and provides a summary of ongoing studies to identify and address these concerns.

Varaiya (2) identifies five aspects of IVHS development: function, architecture, design, evolution and evaluation. Evolution is defined as the timing of system development and deployment, and the extent to which the architecture should accommodate new functions not included in earlier designs, while evaluation is defined as the effectiveness, costs and benefits of different IVHS proposals. Varaiya's paper focuses on the first three aspects of design.

Though not addressed explicitly, many authors have discussed general premises regarding evolutionary development of IVHS. For example, auto manufacturers (3, 4) typically focus on the extent to which individuals are likely to purchase automation equipment prior to the construction of the Automated Highway System (AHS) infrastructure (or at least prior to conversion of lanes from manual to automatic).

Heinrich (3) believes that "the ultimate success (of IVHS) will be highly dependent upon the acceptance and continued use of in-vehicle IVHS equipment by the vehicle driver." The author also links "smart vehicles" and "smart highways" and argues that smart highways have to exist before smart vehicles become a reality. He also asserts that car buyers are generally conservative on what they buy and are looking for practical solutions for their needs, and argues that "the capability of the IVHS infrastructure to provide timely and credible traffic advisories will play a key role in forming and more importantly maintaining the buyer's interest in IVHS."

In an earlier paper entitled "Automated Urban Freeways: Policy Research Agenda," Johnston et al (5) proposed five stages for deployment of automated freeways:

1. Voluntary on-board navigation and route-guidance devices;
2. On-board longitudinal control;
3. Lateral control and dedicated lanes; Table 1
4. Full automation of some lanes;
5. Full automation of all lanes.

Their paper, however, didn't specify how these stages are to be deployed nor did it address the stimulus by which the development would move from one stage to the next.

Hall (6) provides a progression in the development of the highway infrastructure. Different versions of the AHS, including AHS without automated lane change, or with automated lane change at reduced speed, are presented. These are evaluated with respect to

Table 1.1 A SELECTION OF POTENTIAL IVHS MILESTONES* (CONT.)

		1992 – 1996	1997 – 2001	2002 – 2011
AVCS Advanced Vehicle Control Systems	Research and Development	■ Sensors ■ Collision warning ■ Driving simulators	■ Perceptual enhancement systems ■ Vehicle/driver monitoring systems	■ Collision avoidance systems ■ Obstacle avoidance systems ■ Automated network operations
	Operational Tests	■ Roadway/environment safety warning systems ■ Intelligent cruise control ■ Test facility development	■ Collision warning systems ■ Automated highway demonstration ■ Lane departure control ■ Intersection hazard warning	■ Automated freeway lane operation ■ Automated HOV
CVO Commercial Vehicle Operations	Research and Development	■ Weigh-in-Motion ■ Electronic toll collection ■ Driver warning systems ■ Electronic record-keeping	■ HAZMAT cargo information systems ■ Automated vehicle and driver safety inspections	
	Operational Tests	■ AVI/AVL in multiple applications ■ Electronic credential checking ■ Electronic permitting	■ Electronic record keeping	■ Automated heavy vehicle lane testing
APTS Advanced Public Transportation Systems	Research and Development	■ Customer interfaces ■ Customer service systems ■ HOV verification ■ Electronic fare collection	■ Interactive displays ■ HOV guide controls ■ Smart Cards	
	Operational Tests	■ Kiosks ■ Audio/video text ■ Portable traveler information ■ Fleet management systems ■ Maintenance tracking systems	■ Interactive customer service systems ■ Integration of customer and fleet management information	■ Automated transit vehicle operation on specially equipped (HOV) lanes

* Source: Strategic Plan for IVHS [1]

Table 1.1 A SELECTION OF POTENTIAL IVHS MILESTONES*

		1992 – 1996	1997 – 2001	2002 – 2011
ATMS Advanced Traffic Management Systems	Research and Development	▪ Traffic monitoring hardware and software ▪ Traffic control systems logic ▪ Database specification ▪ Traffic management center user interfaces	▪ Multi-source traffic data fusion ▪ Predictive traffic modeling ▪ Dynamic optimal routing strategies ▪ Adaptive traffic control	▪ Site-specific refinement of applications and technologies
	Operational Tests	▪ Traffic monitoring systems ▪ Vehicles as probes ▪ Traffic control systems ▪ Incident detection and management ▪ Traffic modeling ▪ Traffic management center operations	▪ Network-wide traffic optimization ▪ Area-wide traffic management	▪ Multiple transportation mode information integration
ATIS Advanced Traveler Information Systems	Research and Development	▪ Navigation software ▪ Map and business/tourist services databases ▪ Communication alternatives	▪ Dynamic, optimal route guidance ▪ Portable information systems ▪ In-vehicle signing	▪ Multi-modal trip planning
	Operational Tests	▪ Navigation route planning and guidance ▪ AVI and AVL in various applications ▪ Alternative presentation and delivery modes	▪ Dynamic route guidance ▪ Emergency Mayday ▪ Safety/warning systems	▪ Demand-responsive system capabilities

* Source: Strategic Plan for IVHS [1]

their ability to reduce congestion at highway bottlenecks. The paper does not address evolution in vehicular technology.

Tsao and Hall (7) developed an influence diagram representing uncertainties affecting the deployment of AHS (Figure 1). These uncertainties include: technological feasibility; opposition of special interest groups, and inability of auto makers to provide the needed automation. The study synthesizes expert opinions "to identify the critical issues, technical or not, that need to be resolved to ensure timely and efficient deployment of AHS." The influence diagram reflects the staged aspect of AHS deployment, as progress on deployment cannot occur until institutional issues are resolved.

Ward (8), as part of the AHS Precursor Analysis effort, developed an evolutionary strategy in some detail, emphasizing motivations for consumers to purchase at each stage of evolution. He hypothesizes that Intelligent Cruise Control will be the first step toward the automated highway. He also suggests that vehicles, if appropriately designed, might be enabled to form "spontaneous platoons", providing capacity increases.

Ioannou et al (9) define a series of evolutionary configurations as part of their AHS PSA effort. The authors emphasize the evolution of lateral and longitudinal control, taking technological feasibility and capacity and safety benefits into consideration. The result is a series of five evolutionary stages, which gradually automates the vehicle and shifts control to the roadway.

Al-Ayat and Hall (10) developed a framework for planning evolutionary deployment of IVHS technologies. It defines an evolutionary deployment sequence, identifies baseline assumptions, and develops an evaluation framework, consisting of strategy development, strategy evaluation, technology and barrier identification and strategy refinements. This framework provides a foundation for cost/benefit evolutionary strategy, to be presented later.

As a whole, the literature on evolutionary deployment aims to develop plausible scenarios under which today's conventional highway might evolve toward full automation, without incurring unreasonable costs along the way. The strategy developed in this report continues in this vein, while emphasis on building up a fleet of equipped vehicles prior to major investments in AHS infrastructure.

CHAPTER 3. CRITERIA FOR EVOLUTIONARY DEPLOYMENT

This section outlines groundrules (i.e., constraints) for evolutionary deployment, as defined in Al-Ayat and Hall (10). These groundrules are partially based on the FHWA Precursor System Analysis Broad Area Announcement (BAA). The FHWA groundrules are supplemented to

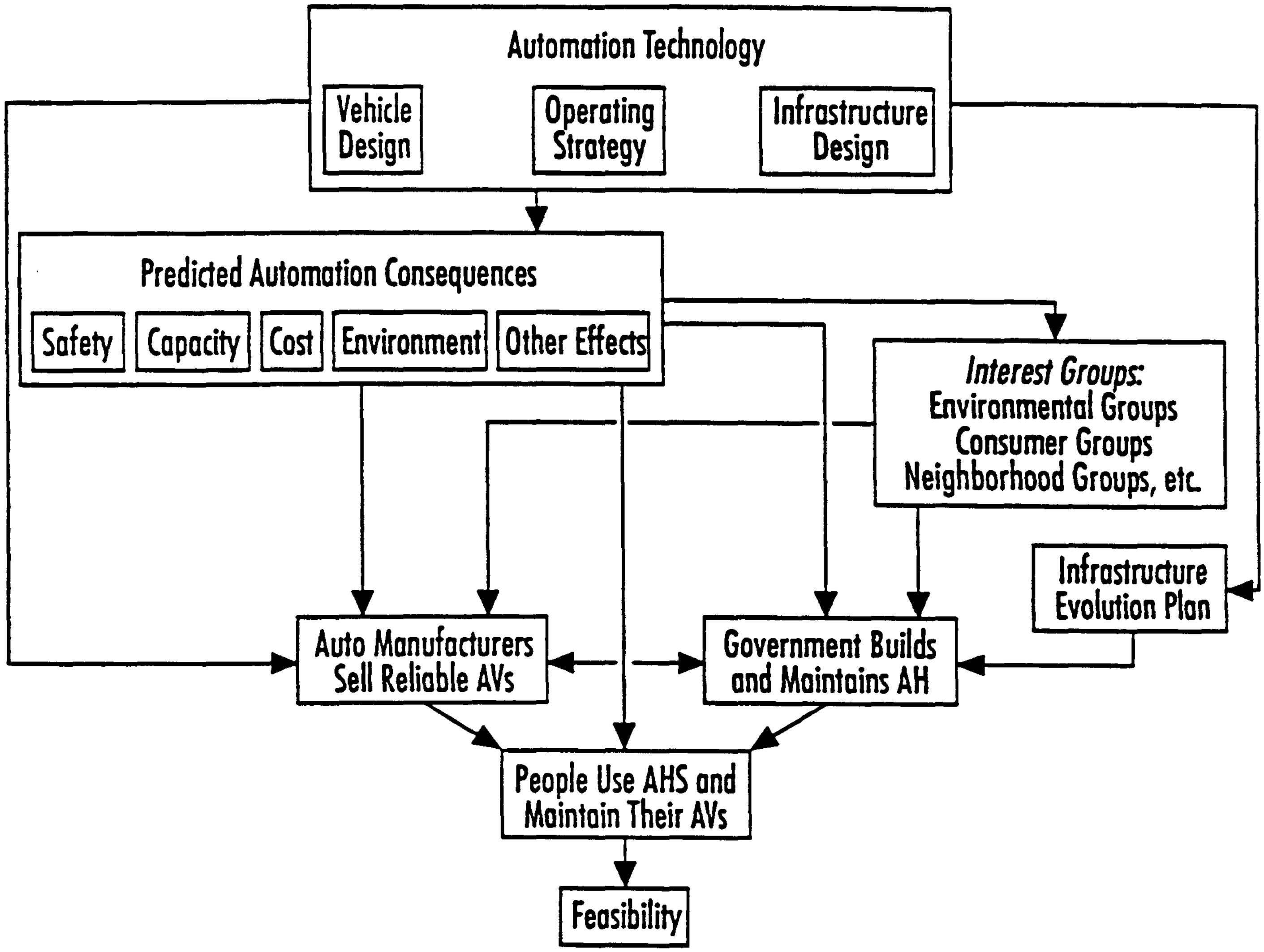


Figure 1: AVCS Feasibility Influence Diagram

explicitly account for the evolution of AHS functions. The complete set of groundrules are the basis for the evolutionary deployment strategy used in the cost/benefit analysis.

The BAA constraints, together with others that are necessary for developing evolutionary deployment strategies, are presented here (Constraints 1 through 4 are adapted from the FHWA list):

1. All vehicle types (automobiles, buses, trucks), although not necessarily intermixed, must be supported in the mature system. Initial deployment emphasis will be on automobiles and vehicles with similar dynamics and operating characteristics.

2. Not all vehicles nor roadways will be instrumented.

3. An AHS will perform better than today's roadways in all key areas including safety, throughput, user comfort and environmental impacts.

4. IVHS technologies will operate in a wide range of weather conditions typical of those experienced in the continental U.S. These include snow, low-visibility fog and heavy rain conditions.

5. Vehicle equipment provides substantial user benefits, even where AHS is not implemented. User benefits could include enhanced performance, or driver comfort. These benefits are needed to motivate drivers to acquire the equipment and to provide sufficient incentive for manufacturers to invest in tooling and infrastructure needed to produce the needed technologies.

6. Automation does not require demolition or relocation of houses/businesses or result in negative impacts on neighborhoods surrounding a freeway.

In summary, automation should strive for the capability to operate at much higher capacity, without increased delays, with much higher safety and energy savings, and with a decrease in pollution. Moreover, automation should be introduced in an equitable manner and, ideally, should not cause any loss or penalties to any individual or group.

An evolutionary deployment strategy should also provide users with increased functionality over time, according to the following guidelines:

7. Full vehicle automation requires minimal retrofit to vehicles designed to operate in low traffic environments in order to operate within a high capacity AHS environment. However, the functions available at each step are useful by themselves, and do not require retrofit to provide significant benefits.

8. Each development step has a high likelihood of acceptance by the user and by the public.

9. Success in each step increases the chance of public acceptance of the following development step.

10. Development steps take into consideration the long lead-time requirements for research and development prior to deployment.

11. Increasing functionality can be achieved without the need for discarding major portions of the system.

As a group, Criteria 7-11 provide one strategy in which AHS is built incrementally, with each step carefully planned, from both a technical and institutional perspective, to lead toward the endpoint.

CHAPTER 4. DIMENSIONS OF EVOLUTION

Evolutionary deployment can be defined along two principal dimensions:

1. Product development cycles
2. Market penetration cycles

The product development cycle leads to the technology's introduction into the marketplace, and includes the following steps (some of which may occur simultaneously):

Research
Proof of Concept Development
Operational Testing
Design for Manufacture
Education
Technical Standards Development
Legislation

The market penetration cycle begins when the product is first introduced, and can be divided into the following steps:

Introduction
Growth
Maturity
Decline

For any component technology of AHS, it is possible, and desirable, to plan for an evolutionary sequence through the steps of product development and market penetration. Such a plan could be used to develop cost estimates for AHS research and development, and to assess the effectiveness of governmental and private expenditures over time. However, to keep cost analyses within bounds, our emphasis will be on the evolutionary steps associated with market penetration.

With respect to market penetration cycle, each component technology may progress through a distinct sequence of introduction, growth, maturity and possibly decline. At any point in time, one technology may be in the introduction phase (perhaps autonomous lane keeping), another in the growth phase (perhaps automated inspection), and another in the mature phase (perhaps Advanced-Integrated-Cruise-Control). Hence, the evolutionary deployment strategy is not just concerned with the initial introduction of the technology, but also with how the technology spreads across classes of users and across regions.

Put another way, the ultimate success of AHS, or any intermediate technology, hinges on introducing technologies into the right markets so that future growth can be sustained. This in turn depends on achieving sufficiently large up-front benefits to justify initial investments while not stretching the technologies beyond safety limitations. For example, autonomous vehicle control might first be implemented on highly traveled, but uncongested, intercity freeways, frequented by business travelers. Comfort would then be a major benefit, which may induce motorists to invest in necessary in-vehicle technologies. Once market penetration becomes sufficient, the technology could then spread to lower traffic roads and lower-end users. Once safety is proved, the technology might spread to congested roadways, with the goal of increasing capacity. The underlying concept is that operation under less stringent low-traffic conditions can lead to refinement of the technology, for eventual operation under stringent conditions. Most importantly, a critical mass of users is likely needed before, first, special facilities are constructed and, second, existing roadways are converted to automation (Table 2).

System Versus Technology Evolution

AHS comprises a vast set of component technologies. Because these component technologies must ultimately work together as a system, our evolutionary deployment strategies will be defined by how the system evolves with respect to the functions it performs, using a framework developed in Hall (11).

According to this framework, the system contains three principal entities, vehicle, driver and roadway/infrastructure. Each entity contains five basic elements: (1) sensing, (2) intelligence, (3) memory, (4) actuators and (5) communication. These elements and entities work together to perform the tasks of driving on a highway, which are principally the following:

Cruising: Maintaining desired separation and velocity; steer to follow center of lane; accelerate and decelerate to accommodate other vehicles or to avoid obstacles.

Lane Maneuvering: Steer into desired gap in adjacent lane without conflicting with adjacent vehicles or objectives. Select most efficient lane of travel.

Exiting/Entering: Set trajectory that allows splitting from current roadway and merging into another roadway while avoiding vehicle or objects, or perform transition to/from automated driving. Check in or check out, with associated inspections, as necessary.

Path Choice: Select most efficient roadway between a selected origin and destination. This last task is largely independent of highway automation, falling more in the category of advanced-traveler-information-systems. Therefore, it will not be covered in the evolutionary deployment strategy.

Using the framework, the highway system of today can be depicted as in Table 3. Most of the intelligence resides with the driver, who is responsible for all of the driving tasks. This same framework will be used to define the steps of evolution in the following sections.

CHAPTER 5. EVOLUTIONARY STRATEGY FOR COST/BENEFIT STUDIES

To satisfy the criteria for evolution outlined in Section 3, it is desirable to build up a critical mass of AHS vehicles prior to extensive deployment of AHS infrastructure. We propose accomplishing this goal through the development and sale of an "AHS Ready Vehicle" (ARV).

An ARV is modularly designed, allowing easy installation, after point of sale, of supplemental sensors and communication devices. Its controller is re-programmable, either via software or plug-in replacement of integrated circuits, to respond to additional sensor and communication inputs. At point of sale, the ARV does possess electronic steering, braking, and throttle control; a flexible driver interface; safety diagnostics; and adaptive-cruise-control (ACC), and

Table 2 Market Penetration

	Introduction	Growth	Maturity
Incentives for User to Purchase	Comfort Convenience Energy Savings Enjoyment Performance Safety (subsidy?)	Travel Time Savings Others (subsidy?)	Travel Time Savings Others (subsidy?)
Infrastructure	Minimal (Autonomous Vehicles)	Limited Special Facilities	Roadway Conversion & Special Facilities
Local Market Penetration	Very Small (<5% of vehicles on the road)	Small (5-20%)	Moderate to High (20%+)

Table 3. CONVENTIONAL VEHICLE ON CONVENTIONAL ROADWAY

CAPABILITIES

	Vehicle	Driver	Roadway
Sensors		Vehicles/Adjacent Lanes Vehicles/Same Lane Obstacles Hazards Weather Conditions Vehicle Condition	Traffic Conditions
Intelligence		Cruising Lane Maneuvering Lane Choice Speed Regulation Exiting/Entering	
Memory		Rules of the Road Driving Skills	
Actuators	Hydraulic Brake Conventional Throttle Hydraulic Steering		
Communication	To Drivers -- Vehicle warning lights	To Drivers -- Turn Signals	To Drivers -- Traffic Conditions (CMS,HAR)

automated steering capabilities (the latter of which can only function on designated inter-city roadways because lane referencing systems must be installed, and to minimize safety risk).

The ARV is capable of operating on a fully automated highway, if retrofitted at modest expense. At the same time, an ARV provides immediate driver benefits, in the forms of comfort and performance. These benefits must be sufficient to motivate a substantial percentage of drivers to purchase an ARV, whether or not extensive AHS infrastructure is ever deployed. These benefits must also motivate purchases across the country, and not just in the locations where fully automated guideways are constructed, in order to achieve scale economies in ARV manufacture.

From the standpoint of roadway infrastructure, we propose that AHS be first deployed on roadways connecting urban centers. The "Auto-Steering AHS" would provide a lane referencing system, which would enable ARVs to operate in a fully automated mode with large inter-vehicle spacing (assuming that a minimum spacing is regulated in manufacture). These initial AHS would not provide capacity gains, but would, at relatively modest cost, motivate ARV purchases. They would not, for instance, have inspection facilities, and vehicle-vehicle communication would not have roadside controllers to regulate speeds or lane changes. They would, however, provide an opportunity for testing and refining AHS technologies, prior to their deployment under more demanding conditions.

The next stage, AHS1, would enable vehicles to operate under close headways within platoons on isolated AHS lanes. Vehicles would enter the lane through manual lane changes into inter-platoon gaps. Capacity would increase, but not nearly so much as possible with automated lane changes. As with ARV, AHS1 would provide a testing ground for advancement to the next stage of evolution.

The final stage, AHS2, enables automated lane changes as well as side-by-side operation of automated and manual lanes (perhaps separated by non-continuous barriers). This is the most technologically challenging stage, which might only be achieved after years of experience operating AHS1. It would also provide the biggest capacity gain, as well as cost savings in construction, because AHS lanes would not have to be completely isolated. Optimistically, if AHS technology advances rapidly, then the AHS1 stage might be skipped, moving directly from AHS1 to AHS2.

Evolutionary Scenario

Building from the "catalysts" of the AHS Ready Vehicle, and the Auto-Steering AHS, the evolutionary strategy is filled out below, from the vehicle and roadway perspectives. At any point in time, we recognize that the fleet of vehicles operating in the United States will contain a mix of capabilities, categorized into the following four stages:

<u>Vehicle Types</u>

(1) Basic: No automation capabilities (other than basic cruise control), and no possibility of retrofit for automation.

(2) ARV: Possesses automated adaptive cruise control and drive-by-wire, and can be retrofitted for full automation at reasonable cost.

(3) AHS1: Able to operate in fully automated mode under high volume, but not able to automatically change lanes.

(4) AHS2: Able to operate in fully automated mode, and to change lanes under full automation.

In addition, at any point in time, the United States highway system will contain a mixture of roadway types, categorized into the following five stages:

Roadway Types

(1) Basic: Conventional highway, with IVHS functions limited to ramp-metering, loop-detectors and changeable message signs (at most).

(2) Roadway-Vehicle Comm: Roadway-vehicle communication is provided, primarily to support traveler advisor and route planning functions, but upgradeable to support AHS

(3) Auto Steering: In addition to roadway-vehicle communication, a lane referencing system is installed to support automated steering. Fully automated driving is allowed under low volume conditions for all vehicle types (i.e., lane referencing is only installed on designated roadways).

(4) AHS1: AHS lanes are isolated from conventional, and allow fully automated driving for automobiles and light trucks and vans under high volume conditions. Automated inspection is provided. Automated lane changing is not supported.

(5) AHS2: Automated lane-change and lane merging is provided. Furthermore, automated lanes do not have to be completely isolated from conventional.

These stages are expanded on in Table 4.

Table 4. ROADWAY CATEGORIZATION

No Enhancements

Conventional highway, with IVHS functions limited to ramp-metering, loop-detectors, and changeable message signs, at most. Only completely autonomous vehicle functions are supported.

Roadway-Vehicle Communication

Roadway-vehicle communication is provided, to support traveler advisory and route planning functions. Roadway conduits are constructed to support land-side communication. Roadway may also contain automated inspection facilities, and the ability to communicate roadway condition information.

Supports Automated Steering

In addition to communication systems, lane referencing and preview information is available to support automated steering. Roadway condition sensors (e.g., ice, wet pavement) are provided as needed for safety. Facility operates under low volume conditions.

AHS Stage 1 Facility

Lanes are isolated from conventional traffic and from each other. Entrance, exit and lane-change occur at designated locations only, under manual operation. Construction of new facilities is required, either along existing or along new right-of-ways. These facilities include automated inspection at entrances.

AHS Stage 2 Facility

Lanes no longer need to be completely isolated. Automated lane-change is provided, and automated lanes can operate adjacent to conventional lanes through common entrances and exits (though barriers, with openings, may exist between lanes). All vehicles entering the highway (conventional or automated) must pass through automated inspection stations.

Assignment of Functions

For the Stage 1 vehicle, and Stage 1 and 2 infrastructure, the vehicle will operate more or less as it does today, under manual control. Stages 2, 3 and 4 vehicles, and Stages 3, 4, and 5 infrastructure, demand a shift in control from the driver to the vehicle, and to the roadway.

The following outlines functions for fully compatible systems; that is, where the vehicle and the infrastructure are at compatible stages of development. It should be recognized that the functionality is limited by the minimum of the vehicle and roadway capabilities (e.g., an ARV cannot operate on AHS1 or AHS2 without upgrade, and an AHS1 or AHS2 vehicle performs the same as an ARV on an auto-steering roadway).

Table 5 outlines the AHS Ready Vehicle operating on an auto-steering roadway. The vehicle has actuators for electronic steering, throttle control and braking. It also has associated sensors and intelligence to allow automated driving under controlled, low traffic, conditions (e.g., on rural highways). On the other hand, the vehicle does not have a complete array of sensors, and vehicle-vehicle communication, to enable automated travel under high flow conditions. This would require retrofit, through installation of sensor and communication modules within a defined architecture.

Table 6 outlines the AHS1 vehicle operating on the AHS1 roadway. This stage adds automated check-in/check-out, with vehicle diagnostics. Vehicle-vehicle communication is also provided within lanes, between leaders and followers, to exchange information on acceleration, velocity, jerk, and location. It also provides additional sensors installed on the roadway to check for weather conditions. Finally, it provides for speed regulation, through commands issued from the roadway.

Table 7 outlines the AHS2 vehicle operating on the AHS2 roadway. This stage adds communication to and from vehicles in adjacent lanes, in combination with improved side sensors, to enable automated lane changes. In addition, the infrastructure now has the capability to issue lane-change commands, based on global traffic conditions.

Operating Concepts

For the purposes of cost benefit analysis, it is not necessary to completely define the AHS operating concept, with respect to such issues as platooning versus no-platooning, lane assignment strategies, and system architecture. These factors only indirectly affect cost and benefits, which are more closely tied to highway capacity, operating speed and hardware/software. Instead of specifying precise values for capacity and speed, ranges will be incorporated in sensitivity analyses for cost and benefit (to be reported in a subsequent

Table 5. AHS READY VEHICLE ON AUTO-STEERING ROADWAY

CAPABILITIES

	Vehicle	Driver	Roadway
Sensors	Brake Engine Velocity,Accel,Jerk Yaw Angle Vehicle Condition Lane Reference Major Obstacles Distance (to leader)	Vehicles/Adjacent Lane Roadway Hazards Weather Conditions	Roadway Conditions Traffic Conditions
Intelligence	Cruising	Lane Maneuvering Lane Choice Target Speed Regulation Exiting/Entering Path Choice	
Memory		Rules of the Road	Lane Reference System
Actuators	Electronic Brake Electronic Throttle Electronic Steering		
Communi-cation	To Drivers -- Obstacle/Speed Warnings -- Vehicle Condition	To Drivers --Turn Signals To Roadway -- Hazards	To Vehicles -- Steering preview To Drivers -- roadway conditions -- traffic conditions -- hazards

UPGRADE TO AHS1:
Vehicle--to-Vehicle Communication
Automated Vehicle Inspection
Enhanced Side Sensors
Software Upgrade for Longitudinal Control
Software Upgrade for Roadway Control

Table 6. AHS1 VEHICLE ON AHS1 ROADWAY
(No Lane Change)

CAPABILITIES

	Vehicle	Driver	Roadway
Sensors	Brake Engine Velocity,Accel,Jerk Yaw Angle Lane Reference Major Obstacles Distance (to leader) Vehicle Condition	Unusual Hazards	Roadway Conditions Weather Conditions Traffic Conditions
Intelligence	Cruising, with close headway vehicle following	Lane Maneuvering Lane Choice Exiting/Entering	Speed Regulation Entrance Metering System Shutdown
Memory		Rules of the Road	Lane Reference System
Actuators	Electronic Brake Electronic Throttle Electronic Steering		
Communi-cation	<u>To Roadside</u> -- Vehicle condition <u>To Driver</u> -- Enter/Exit commands -- Vehicle condition <u>To Vehicles</u> -- Acceleration,velocity, jerk,location	<u>To Roadway</u> -- Enter/Exit requests -- Hazards <u>To Drivers</u> -- Turn signals	<u>To Vehicle & Driver</u> -- Permissions to enter -- Target speeds -- Enter/Exit commands -- Roadway conditions -- Weather conditions

<u>UPGRADE TO AHS STAGE 2</u>
-- Enhanced side sensors for lane change
-- Enhanced communication unit, to communicate with adjacent lanes
-- Software upgrade for vehicle control
-- Software upgrade for roadside controller, to control lane changes

Table 7. AHS2 VEHICLE ON AHS2 ROADWAY (With Lane Change)

	CAPABILITIES		
	Vehicle	**Driver**	**Roadway**
Sensors	Brake Engine Velocity,Accel,Jerk Yaw Angle Lane Reference Major Obstacles Distance (to leader) Vehicle Condition	Unusual Hazards	Roadway Conditions Weather Conditions Traffic Conditions
Intelligence	Cruising, with close headway vehicle following Lane Maneuvering Exiting/Entering		Speed Regulation Entrance Metering System Shutdown Lane Choice Lane Change Initiation
Memory		Rules of the Road	Lane Reference System
Actuators	Electronic Brake Electronic Throttle Electronic Steering		
Communi-cation	<u>To Roadside</u> -- Vehicle condition <u>To Driver</u> -- Enter/Exit commands -- Vehicle condition <u>To Vehicles</u> -- Acceleration,velocity, jerk,location -- Lane change data	<u>To Roadway</u> -- Enter/Exit requests -- Hazards	<u>To Vehicle & Driver</u> -- Permissions to enter -- Target speeds -- Enter/Exit commands -- Roadway conditions -- Weather conditions

report). Hardware and software cost, on the other hand, are relatively insensitive to the operating concept, and can therefore be calculated independently.

The analysis will recognize that an AHS1 has inherently less capacity than an AHS2, because of the disruptive effects of manual lane changes. These manual lane changes may significantly limit the capacity gains of automation. Hence, a principal motivation for upgrade from AHS1 to AHS2 will be the resulting capacity gain.

Justification for Evolutionary Steps

The evolutionary steps are intended to achieve the objectives outlined in Section 3. Justification is provided below.

1. Support for All Vehicle Types
   - -- Strategy will not replace conventional roadways, which would be available for all vehicle types.
   - -- Low volume inter-city roads would allow all vehicles to be automated.
   - -- High-volume roadways would only allow automobiles and light trucks/vans. This is justified by safety considerations, improved performance, and the high cost of providing separate automated facilities for all vehicle types. Buses could be accommodated on ordinary roadways through HOV preferences.

2. Not All Roadways Will be Instrumented
   - -- Strategy explicitly allows for a range of roadway types.

3. Performs Better with Respect to all Key Areas
   - -- Requires completion of cost/benefit analysis and other system analyses: to be determined.

4. Able to Operate in Wide Range of Weather Conditions.
   - -- Requires technical analyses: to be determined
   - -- However, strategy allows flexibility for different guideway types in different regions.

5. Provides Substantial User Benefits Where AHS is not Implemented
   - -- ARV provides potential benefits of fuel economy, improved maintenance, better performance, and access to auto-steering roadways.

6. No Negative Impacts on Neighborhoods.
   - -- Will be used as a constraint in construction scenarios to be created later, provided that cost is not prohibitive.

7. Minimal Retrofit Cost
   - -- The ARV contains electronic steering, braking and throttle control, longitudinal sensor, and controller. Upgrade to Stage 1 only requires installation

of communication modules, software upgrade and perhaps supplemental sensors.

8. High Likelihood of Acceptance of Each Step
   - By beginning with low volume roadways, the fear factor is diminished, and safety risks are reduced.
   - By not providing capacity gains initially, environmental concerns are less likely to block initial implementation.
   - By keeping governmental costs low initially, tax payer complaints may be reduced.
   - Direct user benefits, in terms of comfort, performance, and possibly energy savings and pollution reduction are provided in each step.

9. Public Acceptance for Subsequent Steps
   - High-volume roadways, and later lane changes, are only implemented after users are familiar with the technology. By then, support could be generated.
   - By beginning small, the system can be tested without embarrassing failures.
   - Strategy does not require conversion of conventional roadways to automated use until there is a sufficient number of equipped vehicles.

10. Consideration of Long Lead Times
   - Simpler technologies are implemented first, so that benefits can be generated while research proceeds.
   - Initially implementations can be used to test and refine more advanced technology.

11. No Need to Discard Major Portions of the System
   - The strategy is modular and incremental, without requiring the vehicle purchaser, or government, to discard investments.

Market Penetration

As already mentioned, evolutionary deployment must account for the fact that market penetration takes time. When a technology is introduced, only a small percentage of new vehicles, and an even smaller percentage of vehicles on the road, will contain it as an option. Taking air bags as an example, in 1992, five years after its introduction, less than 60% of new vehicles sold contained a driver-side air bag, but fewer than 20% of the vehicles on the road had an airbag. This is for a case of unusually fast market growth.

A critical step of the cost/benefit analysis will be to define market penetration scenarios for each evolutionary stage of the AHS vehicle, and for the AHS roadway. Initially, this will be reflected in an increasing percentage of the fleet at Stage 2, and later in Stages 3 and 4 (at which point, Stage 2 may be in decline). However, a large percentage of the fleet may be at Stage 1 well in the future, as some drivers will have no desire to purchase automation equipment. Similarly, roadways will evolve toward higher levels of functionality over time, first to Stage 2, and later to Stages 3, 4, and 5.

Evolution is unlikely to occur at the same pace in all regions of the country. For instance, Stage 3 infrastructure may appear first on highways connecting large urban centers, which will allow drivers to relax during travel. Stage 4 and 5 facilities may appear first in congested cities, and perhaps never in uncongested cities. Evolution of the vehicle fleet will likely parallel evolution of the infrastructure, with vehicle purchasers responding to roadway capabilities. Furthermore, the fleet evolution will occur over a long time period, in accordance to periods of car ownership, demographic characteristics of purchasers, and equipment cost.

CHAPTER 6. IMPLEMENTATION SCENARIOS

Specific implementation scenarios were created for the purpose of cost analysis. These scenarios translated the AHS functions specified in the prior section into specific technologies. Because AHS technologies still require considerable research, the implementation scenarios are somewhat speculative, and represent a best guess based on the state-of-the-art today. Rockwell International was responsible for specifying the electronics for each step in the evolutionary sequence, both for the vehicle and the roadway. Bechtel was responsible for specifying the construction, including means for adding lanes (if necessary), barriers, conduits, and installation of electronic devices on the roadway. The following summarizes the scenarios investigated. Details can be found in Volumes 3 and 4 of the PATH Cost/Benefit Report.

Electronics

Electronics were specified for three configurations: two Minimal Infrastructure Modification (MIM) configurations, and one Infrastructure Intensive (II) configuration. In the MIM configurations, as much of the electronics as practical are placed on the vehicle, and in the II configuration, as much of the electronics as practical are placed on the roadway.

In all configurations, ARV vehicles are allowed to mix with conventional traffic on auto-steering roadways, under low traffic conditions. However, in AHS1 and AHS2, the MIM configurations are differentiated according to operating environment. In one case, automated and manual vehicles operate in mixed traffic, and in the other, automated vehicles operate on dedicated lanes. Note that mixed traffic in AHS1 and AHS2 is inconsistent with the evolutionary scenario presented earlier. They are included here with the purpose of bounding cost, without presuming feasibility and safety. The II configuration, on the other hand, is intended to be deployed on a completely dedicated roadway in AHS1, and on joint-use roadways in AHS2. This means that in AHS2 certain lanes are designated for fully automated vehicles, but these vehicles must pass through manual traffic to reach these dedicated lanes. Joint-use roadways are technically more challenging. Hence, for II, they are only used for the last evolutionary stage (AHS2). Figure 2 schematically depicts the configurations for each evolutionary stage.

AHS Ready Vehicle (ARV) The ARV is assumed to be identical for all configurations, with the following physical elements:

<u>Sensors</u>

- o A Sensor(s) to measure the range to the vehicle ahead in one's lane.
- o A sensor(s) to measure vehicle position in the lane for automatic lane keeping.
- o Sensors for condition of on-board equipment to support self-test and diagnostics.

Intelligence/Memory
- o Computing elements to interpret sensor signals and determine the desired vehicle responses.
- o Internal computing to carry out self-test and diagnostics.

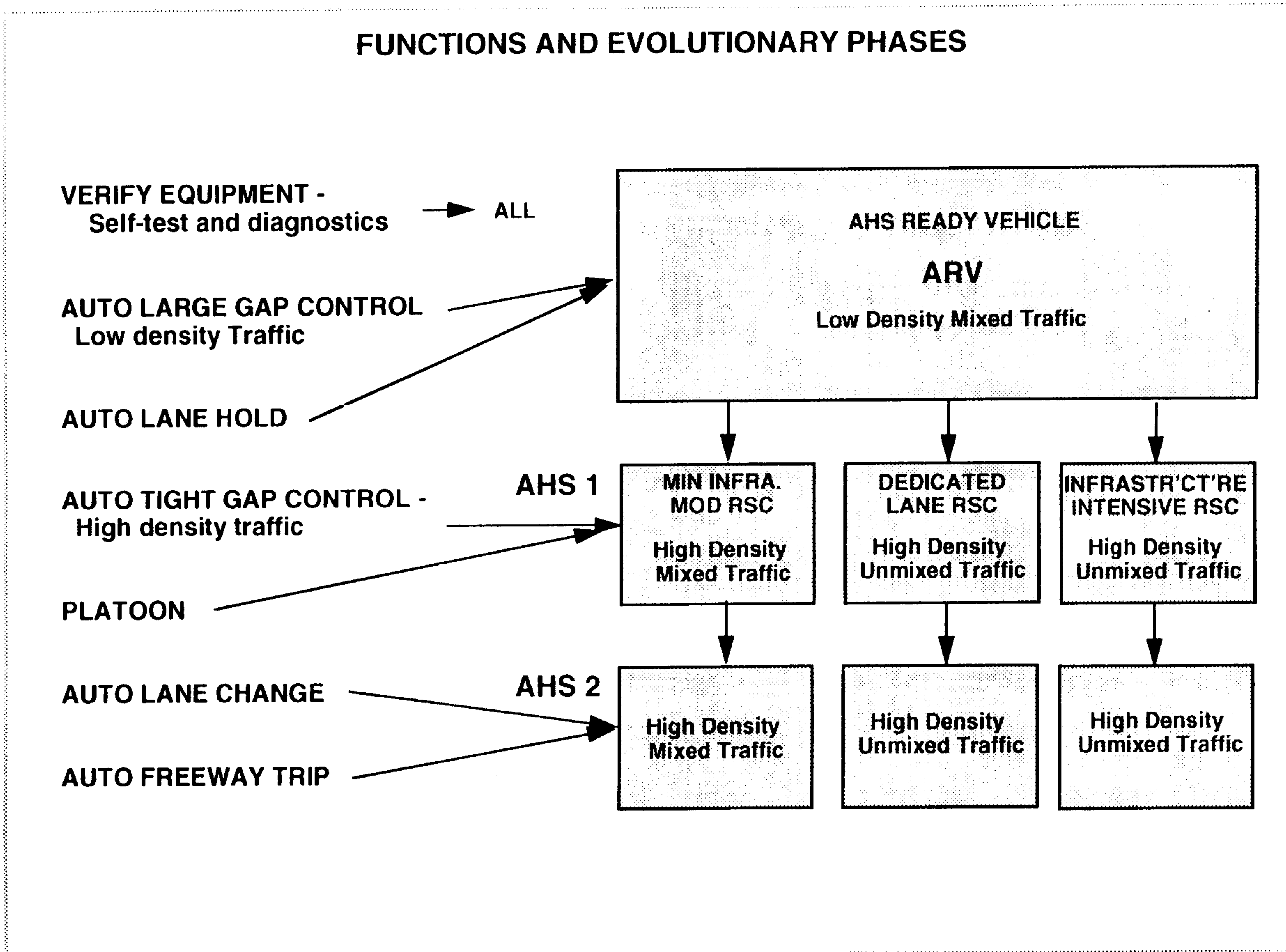
Communication
- o None is assumed.

Actuators
- o Drive-by-wire system components.

Interfaces
- o A driver control interface.
- o An intelligence/command input interface to drive-by-wire actuators.

We envision that these elements will be physically packaged as three subsystems: A Sensor-Intelligence Subsystem, the Drive-by-Wire Subsystem, and the Driver Interface. The self-test and diagnostic elements will be built into each of these subsystems. These are described in detail in Volume 3. Critical elements include a multibeam millimeterwave radar; a magnetic field sensor to track magnetic nails for lane keeping; and steering, braking and throttle actuators for electronic driving.

Figure 2



Rockwell International

AHS1: MIM, Mixed Traffic AHS1 differs from ARV by adding the capability to operate at close following distances in heavy, mixed traffic. (Again, this scenario is included with the goal of bounding cost, without presuming feasibility.) Lane-changing is still manual. These changes require the following upgrades from the ARV system:

- To minimize the following distance required for safety, tight control loop is more critical: sensor detection and processing (sensor interpretation and vehicle response determination), and control actuation would desirably be closer to real time.

- Road conditions are more important, because of shorter following distances, and because the driver is less able to affect vehicle control in hazardous conditions.

- The tactical driving scene is more complex: there is greater concern with the behavior of vehicles in adjacent lanes, and more information must be considered in processing.

- To prevent system failures, redundant sensing is more important.

We therefore have hypothesized the need for the following additions to the ARV system.

- The ranging radar is augmented with a pair of vision-based sensors to permit stereo ranging. Vision-based sensors also permit the tracking of the lane marker lines to provide an independent input for auto lane keeping.

- A rain/snow sensor on the vehicle modifies the allowable following distance in bad weather. There is also the possibility of measure road friction coefficient by observing deceleration response to braking.

- The computational speed and memory requirements of the sensor processing unit must be higher.

- The Self-Test/Diagnosis Unit is more complex.

- Manual control is now completely through the drive-by-wire system.

In addition, platooning requires the addition of vehicle-to-vehicle communication between fore and aft vehicles, with range out to about 30 meters. Some range sensors will also have to operate down to about .3 meter. This might be accomplished by alternative optics for the vision-based sensors, or a new dedicated sensor.

AHS2: MIM, Mixed Traffic AHS2 adds the capability for automated lane changing, and thus introduces the possibility of the fully automated freeway trip from on-ramp to off-ramp. AHS2 adds three new elements to AHS1: first, the ability to do automated lane changes; second, an ability to accept the driver's input of a desired exit ramp; third, a protocol to select lanes and a method of navigating to the desired off-ramp at the end of the freeway trip.

Automatic lane change requires redundant or self checking sensors looking both directly to the side and back in the next lane to measure range and range rate of the nearest vehicle on the rear quarter - essentially 360^{o} coverage. We assume vision-type sensors for costing purposes. The Sensor-Intelligence Unit logic needs to be expanded to include this maneuver.

The navigation input can be either GPS, or messages embedded in the freeway. For example, a code using a combination of magnetic nails could identify each up-coming exit, or an RF beacon. The system could be preprogrammed to select the lane on the basis of trip distance. There will be some slight modification to the Sensor-Intelligence Subsystem to accommodate this input.

AHS1, MIM, Dedicated Lanes We examine here how the provision of dedicated lanes, and therefore the removal of the need to operate in mixed traffic, might impact the AHS1 equipment.

We conjecture that some supplement to the radar assumed for the ARV will be needed to minimize false alarms that will be more serious with the closer vehicle spacing, and that choice will still be passive, vision-based sensing. However, provision of dedicated lanes may counter-balance this requirement. The fact that all vehicles are equipped simplifies the second sensing system by eliminating the need for stereo ranging. For example, we can assume that each vehicle carries a distance measuring reference where it can be seen by the vehicle in back, such as two emitters a fixed distance apart that can be seen by a vision-type ranging sensor. Thus a single vision-based sensor is adequate to provide the necessary redundancy.

AHS lanes are assumed to be separated from conventional lanes by rumble strips or barriers: The law would largely eliminate deliberate entry, but could not eliminate the accidental entry. The only response available to the AHS1 vehicle is braking, so the only useful capability is to be able to detect a large normal velocity component of vehicles in the next lane, whether it be a buffer lane or a lane of ordinary traffic. To either the radar or the vision-based sensor, this appears as a rapid lateral movement of the object in the next lane. This processing is no different than already implicitly assumed for the mixed traffic case.

AHS2, MIM, Dedicated Lanes We assume that the possibility of cooperation in the rearward sensor interpretation problem can reduce processing somewhat; otherwise the problem is the same as with the MIM system. We conclude that the primary effect is the elimination of one of the vision-based sensors. As discussed in Volume 3, the AHS2 processor for mixed traffic is significantly larger than the AHS2 processor where dedicated lanes are available.

AHS1, II, Dedicated Facility In this RSC we assume a multilane facility with at least some of the lanes fully dedicated to automated vehicles. Unlike the MIM dedicated lane configuration, major electronic functions are added to the infrastructure. The possibility is left open that some lanes, at least initially, will continue to be left to manual traffic; this should substantially reduce the cost of initial deployment. We assume that if there are manual lanes, the AHS vehicles will reach their lanes by ramps that open directly into the AHS lanes.

We assume that all intelligence associated with maneuvering is assigned to vehicle control, and that commands to execute speed changes, platooning/deplatooning, lane changes, and exiting maneuvers are initiated by the infrastructure. The most accurate measurement of space between vehicles is obtained from on-board range measurement, and on-board measurement offers the best opportunity for tight-loop control. It would be extremely difficult - perhaps impossible - to maintain the tight control loops needed for safe maneuvering using infrastructure based sensors to observe the scene, to process these data to identify relative motions, to then determine the desired vehicle response, and communicate back to the vehicle the desired brake, throttle and steering actions needed.

The Sensor-Intelligence Unit differs from the ARV in the following ways.

- o As with the MIM configurations, redundancy should be provided in range measurement. But with dedicated AHS lanes, the alternative range measurement system can be simplified as already discussed under the MIM dedicated lane configuration, where we assumed that each vehicle carries a distance measuring reference where it can be seen by the vehicle in back. This eliminates the need for stereo ranging.

- o The self-test and diagnostic unit must have a receiver and transmitter to respond to the auto check-in unit. This is an adjunct function of the basic receiver-transmitter unit.

- o Because the behavior of traffic in the AHS lanes is predictable, and with manual traffic precluded from entering the AHS lanes, there is no need to read turn-signals, nor to measure range on any vehicles other than the one directly in front. This significantly simplifies the processing, both the sensor interpretation and the desired vehicle response logic.

We have retained the backward-looking sensors used to support lane changing, both to provide a back-up safety check when under infrastructure control, and to aid in lane changing while traversing the manual lanes in getting to and from the dedicated AHS lanes.

In addition to the above changes, the introduction of the ability to operate in platoons requires the same changes as in the MIM configurations:

- o Platooning requires the addition of vehicle-to-vehicle communications between fore and aft vehicles, with range out to about 100 feet.

- o The logic built into the sensor-intelligence unit requires expansion to cover the platoon/deplatoon decision and to control the new maneuvers involved.

- o Some range sensors have to operate down to about .3 meter. This may be accomplished by tricks with the vision-based sensors (alternate optics, for example), or a new dedicated sensor may be a preferred approach.

Volume 3 discusses differences in the on-board processor between AHS1 and AHS2.

We assume the system operates as follows. A vehicle goes through rolling check-in on the on-ramp. The check-in unit on the ramp queries the self-diagnostic system on board the vehicle, and assigns the vehicle a unique code to identify that vehicle to roadside sensors and road-to-vehicle communications. The vehicle, in turn, transmits the identification of the desired off-ramp to the Master Control Center (MCC).

There are two types of AHS Control Centers: a Master Control Center (MCC) for some fairly large length of freeway (about 80 km), and a larger number of Local Control Centers (LCCs) spaced at intervals of about one per eight km. The MCC has two primary functions: to oversee the routing and exiting of vehicles, and to perform freeway congestion control. The MCCs directly control on-ramp metering, and coordinate this action with surface street traffic management. They also control (through the LCCs) vehicle speed and spacing, including platooning. Thus, the MCC includes the following subsystems: vehicle monitoring unit, congestion control unit and operator displays.

LCCs receive data from tracking sensors in the vehicle tracking subsystem (addressed below). It receives instructions from the MCC on desired actions for these individual vehicles, and acts to carry out these instructions. It also executes all local zone commands: all changes in speed and vehicle spacing, including platooning. The LCC commands deplatooning when needed for exiting. Under some conditions, the LCC may command upstream vehicles to slow or speed up to create a gap to facilitate lane changing. The LCC consists of the individual vehicle control unit, zone flow control unit, and operator displays.

Highway surveillance units are the source of information to both the MCCs and the LCCs. Congestion control, particularly in response to accidents or incidents, requires local-zone by local-zone regulation of stream speed and density, as well as ramp meters. The required information can be obtained by conventional traffic management type sensors that measure density and velocity. In addition, individual vehicles are identified through a tracking unit, consisting of a vision-type sensor and the interpretation subsystem with the capability to extract the vehicle code, the time, its position and velocity of every vehicle in its vision.

The following different communication data streams need to be accommodated. This may be accomplished through telephone, some form of broadcast, or dedicated hardwire.

- Between vehicle tracking units (VTUs) and MCC's vehicle monitoring unit (VMU).
- VTUs to MCC's congestion control unit.
- MCC's vehicle monitoring unit to the LCC's individual vehicle control unit IVCU).
- LCC's zone flow control unit to vehicle zones.
- LCC's individual vehicle control unit to vehicles.

Detailed requirements are provided in Volume 3.

AHS2, II In AHS2, we add the backward-looking sensors used in the MIM and DL RSCs to support lane changing, both to provide a back-up safety check when under infrastructure control and to aid in lane changing while traversing the manual lanes in getting to and from the dedicated

AHS lanes. Based on analyses in Volume 3, the AHS2 on-board processor is about a third larger than the AHS1 processor, but still only two-thirds the size of the AHS2 MIM RSC processor.

Under AHS2 we can no longer leave the timing and execution of lane change maneuvers to the driver. We assume that lane-changes are executed by the vehicle, but synchronized by LCCs (this may not be most efficient, but is being used for the purpose of bounding cost estimates). We also assume that the LCCs can issue commands to create gaps to accommodate lane changing.

While the communications load may be reasonable, the processing load implied by AHS2 for the Individual Vehicle Control Unit (IVCU) in the LCC is substantial. Now the LCC must analyze the total kinematic problem for every lane change under its purview. This involves near-continuous tracking of the involved vehicles for the duration of the gap creation maneuver and timing the signal to the vehicle to initiate the actual lane change. Again, this concept is only included for bounding costs; likely, it is much simpler to decentralize this process to vehicles.

From the analysis of communication data loading under AHS1, we estimated that each LCC handles 30 actions involving individual vehicles per second. At least half of these are lane changes, which would imply the need to process a lane change maneuver 15 times per second. If each lane change requires, say, 5 seconds, then there are 60 such computations going on simultaneously. We estimate a 5 to 10 increase in processor capability to handle AHS2.

Roadway Construction

In order to transition to a fully mature AHS facility, either existing roadways need to be modified, or entirely new facilities are constructed. This section describe various alternatives which allow conventional and automated vehicles to travel on the same right-of-way. Completely separated AHS facilities can be extrapolated from the scenarios presented here.

The costing of these scenarios was based on a reference roadway: the Hollywood Freeway located in Los Angeles (additional details in Volume 4). We determined that a single "one-modification-fits-all-locations" scheme would not be possible, and that various alternatives would need to be investigated. For instance, where right-of-way is severely restricted, it may be impossible to widen the existing highway, and an entirely new facility might have to be constructed. As another example, it may be feasible to add dedicated AHS on-ramps in some cases; in other cases, AHS vehicles may be forced to use conventional on-ramps, due to construction limitations. To a degree, then, construction considerations might also drive the selection of an electronics configuration.

The following roadway options describe possible adaptations to incorporate AHS traffic.

(1) All four lanes automated with AHS technology. These mayappear and function as normal lanes to non-automated vehicles, or may be entirely dedicated to automated vehicles. Since all lanes are automated, there is no need to physically separate manual from automated traffic (Figure 3).

(2) Add one lane to create a total of five lanes per direction: One lane automated, one buffer lane, and three lanes to remain conventional traffic. Use of this option is severely restricted in some cases, especially well-developed areas, due to the high cost of additional right of way. However it is expected to constitute a particularly useful option in growing areas where traffic volume can be expected to steadily increase with or without the addition of AHS. The buffer lane is largely used for the necessary merging between AHS and conventional traffic and could be the site of some check-in-motion testers (assuming they are flush with the roadway) of AHS requisite equipment, should that equipment become available in the future (Figure 4).

(3) One lane automated, one buffer lane, and three conventional lanes, as described above, but dedicated on/off ramps for automated lane entrances and exits into buffer lane from overhead structures such as bridges. This option has many of the advantages and disadvantages of the preceding option, but reduces weaving on the roadway to access the

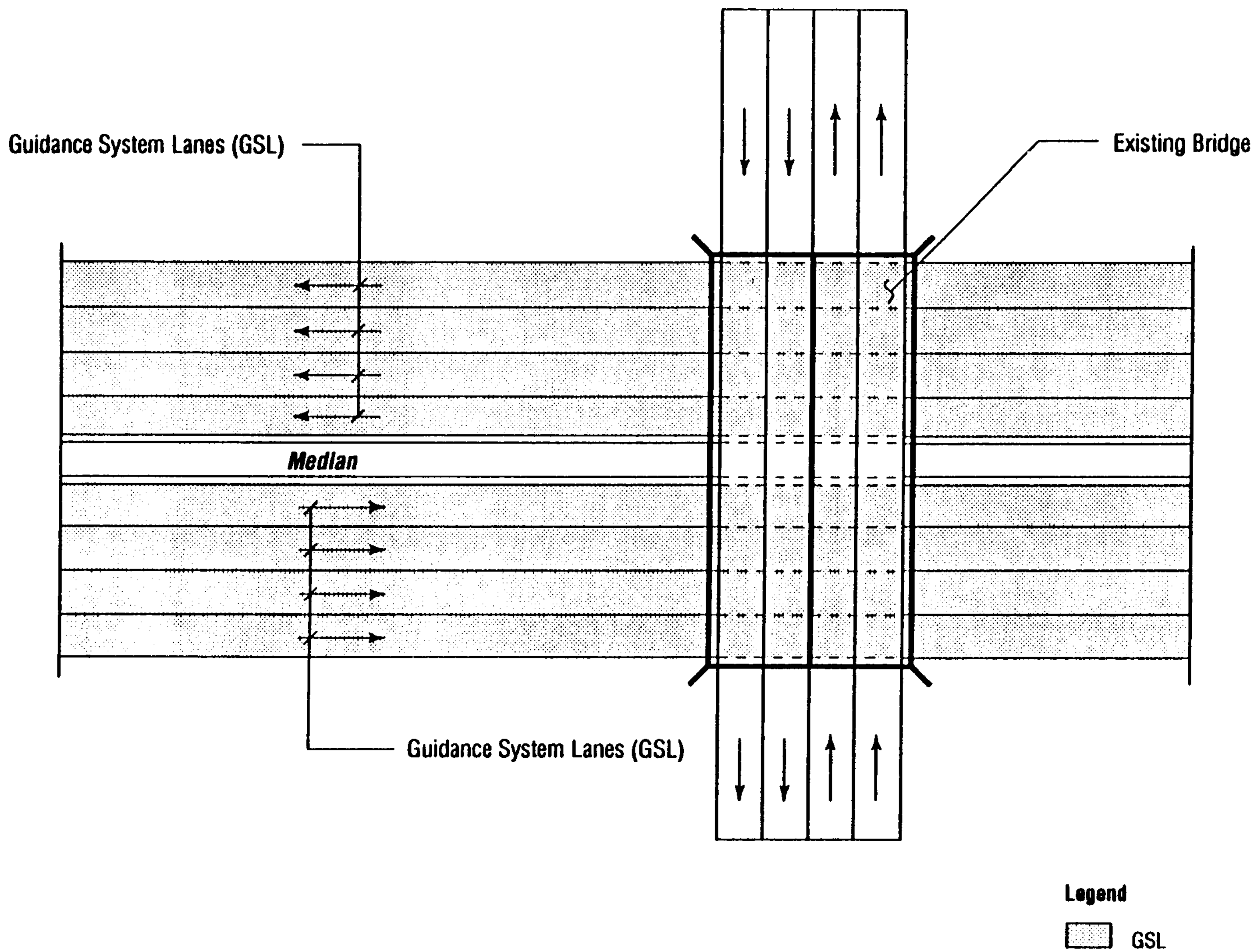


Figure 3

Option 1 All Lanes Automated

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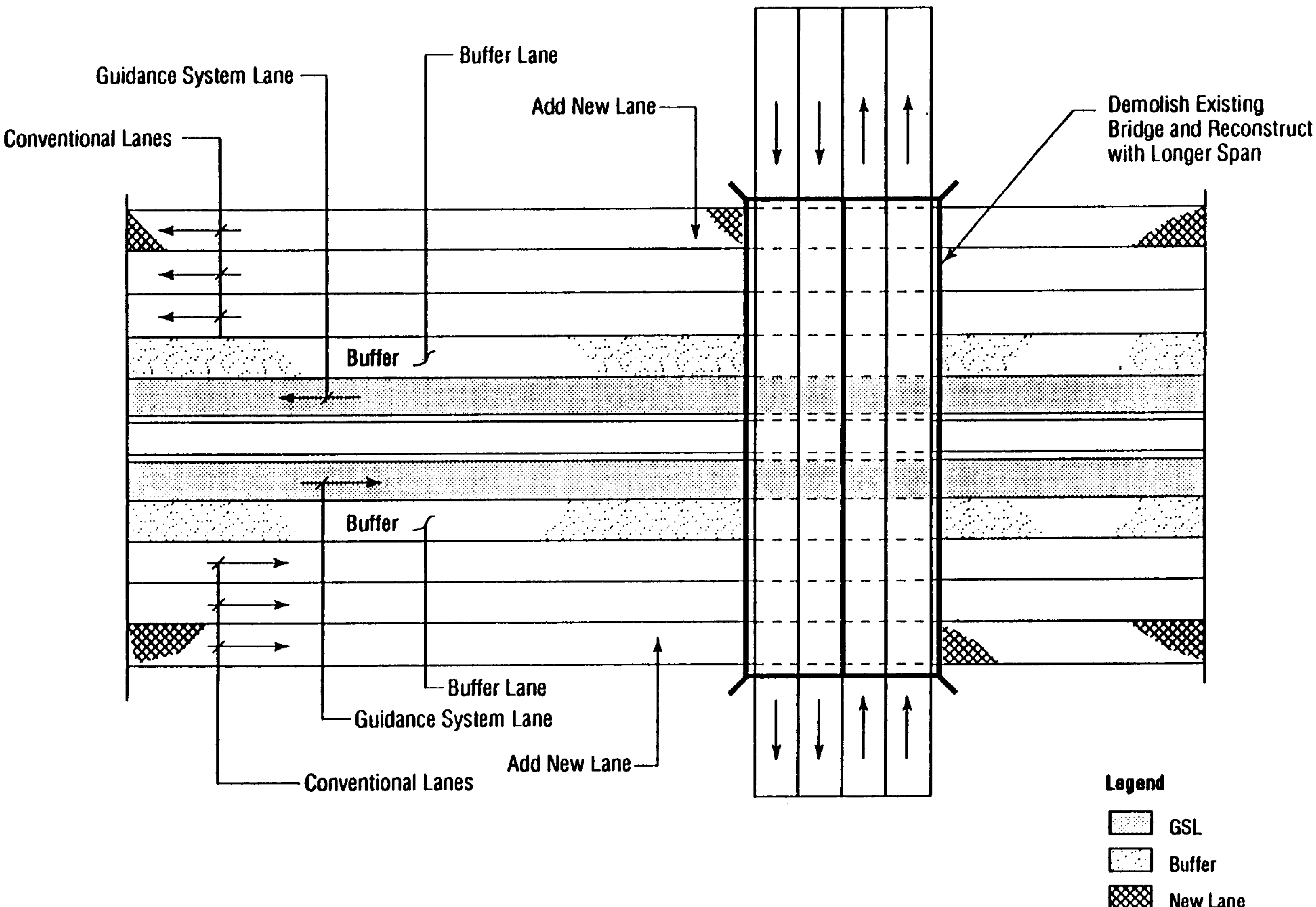

Figure 4

Option 2 One Lane Automated – Three Lanes Conventional
Buffer Lane Added Between Automated and Conventional Lanes

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automated lane. The buffer lane remains essentially unproductive except for its capacity to feed the automated lane. In this option, continuous barricades might be possible between the automated section and the conventional section (Figure 5).

(4) One lane automated, no buffer lane, three conventional lanes, with automated lane delineated from conventional lanes by a rumble strip or special striping. This option follows a precedent in Los Angeles, where striping and signs provide the only demarcation of certain HOV lanes. Exclusion is by traffic enforcement, where substantial fines are levied for violation of the specially designated lane (Figure 6).

(5) Automated lane created on a dedicated structure with its own exit/entry ramps. This structure is anticipated to follow the existing highway right of way for the most part, but exit/entry ramps may be more widely spaced than typically found for conventional roadways to minimize costs and traffic flow interruptions (Figure 7).

New roadway construction along alternate right of ways (e.g. utility corridors) can, in general, be extrapolated from the last option (dedicated AHS structure) presented above.

Table 8 indicates which roadway scenarios are applicable to which electronics scenarios. Question marks appear where the roadway scenario is possibly applicable, given the following qualifiers.

Roadway Scenarios 2 and 4 do not physically separate conventional vehicles from manual vehicles, but do provide dedicated lanes. This is possibly feasible for AHS1, depending on advancements in surveillance and enforcement technologies, to keep conventional vehicles out of automated lanes.

Roadway Scenario 3, which provides dedicated ramps for AHS, is applicable to AHS2 (which allows conventional and automated on the same facility), provided that access is also provided from conventional lanes. Due to added cost, this may be unrealistic.

Roadway Scenario 4, which does not provide a buffer, either requires a manual lane change directly into the automated lane (which is counter to the intention of AHS2, especially if there is a single automated lane), or an automated lane change, in which one of the conventional lanes accommodates automated vehicles before or after lane change (which is counter to the intention of AHS1). Either case is problematic.

Roadway Scenario 5, which provides a dedicated facility, is counter to the intention of AHS2, which allows automated and manual vehicles to travel on the same roadway. However, it's possible that dedicated facilities constructed for AHS1 may be upgraded to AHS2, once automated lane change is provided. Entirely new facilities, on the other hand, are not intended

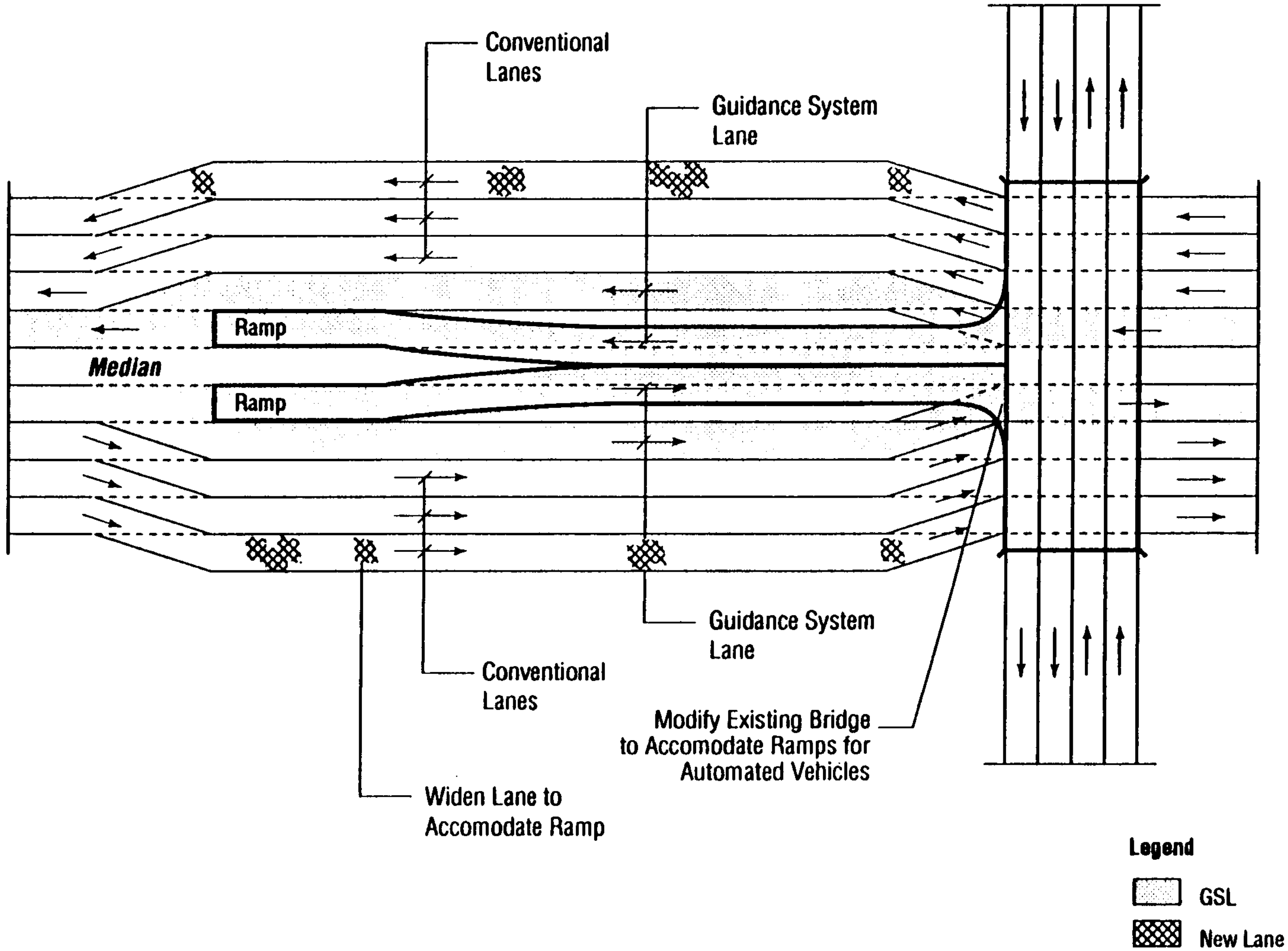

Figure 5

Option 3 (Similar to Option 2) Without Buffer
On/Off Ramps Added with Bridge Structure

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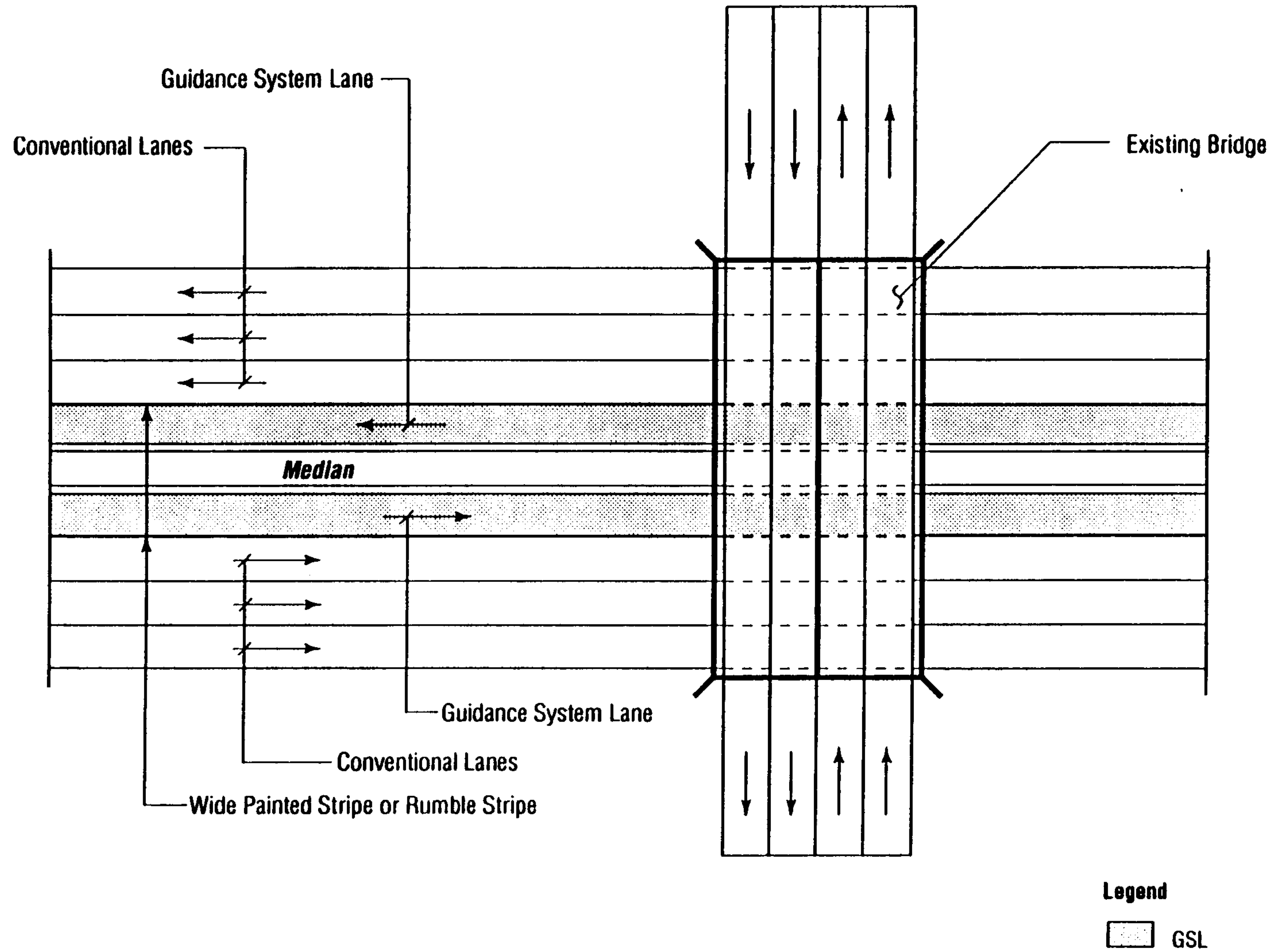

Figure 6

Option 4 One Lane Automated In Each Direction
Three Lanes to Remain Conventional
Separation by Wide Striping or Rumble Strips

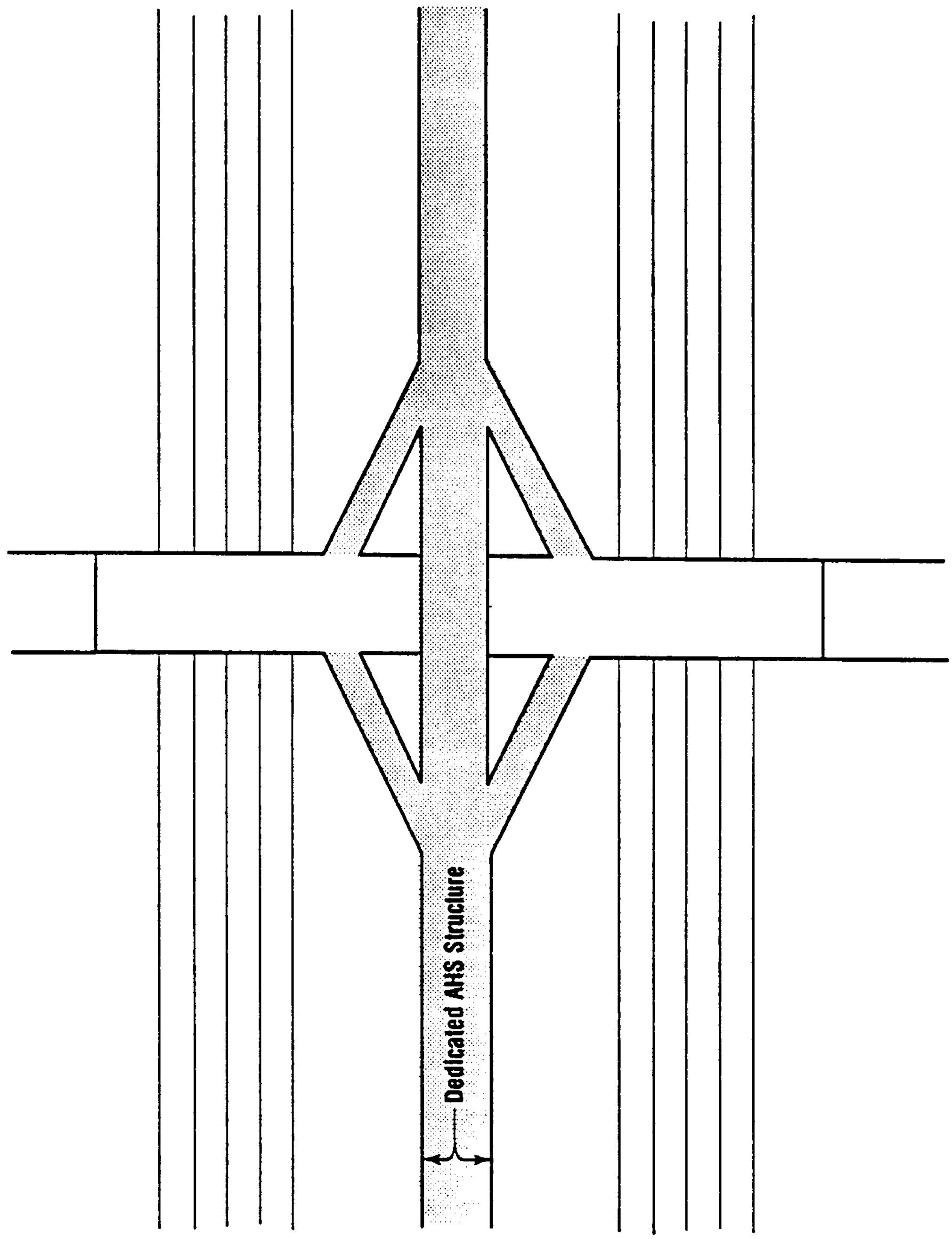

Figure 7

Option 5 AHS Access at Overcrossing – Plan

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Table 8. APPLICABILITY OF ROADWAY SCENARIOS TO ELECTRONICS SCENARIOS

	ELECTRONICS SCENARIOS						
	Mixed Traffic		| ---------Dedicated Lanes-------				
		---Min Infrastructure Mod----				|Infra. Instense	
Roadway Scenarios	ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
(1) All Automated*	X	X	X				
(2) 1 Auto + 1 Buffer				?	X	?	X
(3) 1 Auto + 1 Buffer + dedicated ramps				X	?	X	?
(4) 1 Auto, No Buffer				?	?	?	?
(5) Dedicated Facility				X	?	X	?

Legend

X: Roadway Scenario is Definitely Applicable to Electronics Scenario

?: Roadway Scenario is Possibly Applicable to Electronics Scenario

---

* Alternately, some subset of the lanes might allow automated vehicles.

to be constructed for AHS2. The rationale is economic: if AHS technology is sufficiently advanced, then it would not be worthwhile to incur the added cost of completely segregated facilities.

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Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Electronic Cost Analysis

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-157
March 1995

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

PRELIMINARY COST/BENEFIT FACTORS ANALYSIS

Volume 3
ELECTRONICS COST ANALYSIS

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APPENDICES

PRELIMINARY COST/BENEFIT FACTORS ANALYSIS

Volume 3
ELECTRONICS COST ANALYSIS

This report describes the analysis and resultant predicted acquisition and ownership costs for AHS electronic equipments. Equipment suites and associated costs are presented for vehicle and infrastructure electronics covering several evolution stages and Representative System Configurations (RSCs).

Section I: METHODOLOGY DESCRIPTION

The overall study approach to develop the data contained in this report is depicted in Figure I - 1. and described in the following paragraphs. The study flow as shown in Figure I - 1 involved the identification of AHS functional requirements, the translation of these requirements into representative physical solutions , identification of current and ultimate hardware products which satisfy those solutions, and the estimation of future acquisition and support costs associated with those products. Costs are presented as a function of acquisition year and market size.

AHS Electronics
Cost Estimating Methodology

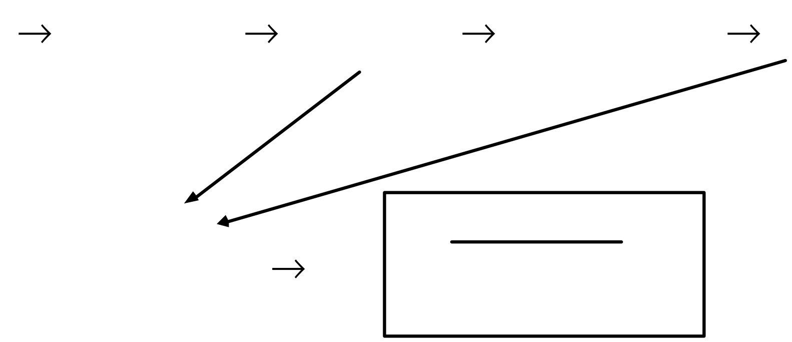

Figure I - 1. AHS Functional Definition and Cost Estimating Study Flow

Step 1: Define the Functional Evolution of the System

We use the evolution defined by PATH. The first step is the introduction of the AHS Ready Vehicle (ARV). An ARV is a vehicle capable of fully automated safe following and lane keeping on minimally modified existing facilities. ARVs are mixed with ordinary, manually-controlled vehicles. The technical requirements are made less stringent by restricting operation to large following distances in low volume traffic: the conditions that obtain most commonly in intercity travel. An ARV is fully equipped for drive-by-wire operation, and is designed insofar as is practical to accommodate successive upgrading of its intelligence functions to the AHS1 and AHS2 levels of operation described below.

The second major step in evolution is to the AHS1, which is capable of hands-off cruising at short headways in high volume traffic, but depends on manual lane changing.

The third step is to AHS2, which is AHS1 with automated lane changing.

Step 2: Select the Representative System Configurations (RSC's)

Three RSC's have been selected that are considered to span the spectrum of practical operating philosophies and distributions of electronics between the vehicle and the infrastructure.

At the ARV stage of evolution all three of these RSCs share the same technical mechanization, but as we advance to the AHS1 and AHS2 stages of capability the technical paths diverge.

The first RSC defined is the Minimum Infrastructure Modification (MIM) RSC, in which the vehicle is designed to continue operating on existing freeway facilities with very little modification, sharing those facilities with unmodified, manually controlled vehicles. It is the ARV, but with the restriction to only light traffic flows removed. As with the ARVs, the AHS1 and AHS2 vehicles are essentially autonomous, using on-board electronics, receiving only traffic advisories from the Traffic Management System (TMS), and operating in any lane. Self-test and driver warnings substitute for check-in inspections.

The second RSC might be called a Dedicated Lanes (DL) RSC. The sensing and electronics are still largely Vehicle-based, but the requirement to operate in mixed traffic is removed by providing lanes dedicated to only AHS1 and AHS2 vehicles.

We note here that without the ARV as the first step, there would be the difficulty of justifying the allocation of dedicated lane space before there are a reasonable number of vehicles equipped to use it, and the difficulty in inducing people to buy equipped vehicles when there are still few dedicated lanes to accommodate them: the classic chicken and egg problem. ARVs - which do not require dedicated lanes or other facilities - should appeal to people who do extensive intercity driving, so offer a way to proliferate vehicles that could be quickly upgraded to take advantage of new dedicated lanes, and thereby help justify their introduction.

In both the MIM and the DL RSCs, the electronics are on the vehicle; the only difference is that one can operate in mixed traffic and the other does not. The two, therefore, provide a first cut at estimating the impact of the mixed-traffic capability on vehicle electronics, which was, in fact, the motivation for including the DL RSC. Obviously this increment in the cost and complexity of the on-board electronics is balanced against the cost and complexity of providing the dedicated lanes. And because dedicated lanes will not be made available everywhere the potential market is curtailed in the DL scenario. This will also impact costs because it cuts the number produced, but we make no attempt to evaluate this countervailing impact.

The third RSC is the Infrastructure Intensive (II) RSC which assumes, except in the introductory phase of ARVs, both dedicated lanes and as much of the electronics moved to the infrastructure as we consider practical: we have accorded to the infrastructure the maximum practical control over the vehicles. In this mechanization the infrastructure makes almost all routing, speed, gross spacing, platooning/deplatooning, lane change, and exit decisions; for reasons discussed later the lane holding and the safe spacing functions are still based on vehicle-mounted sensors.

Figure I - 2 schematically depicts this hypothesized evolution, showing the major system functions and their relationship to the evolutionary steps described.

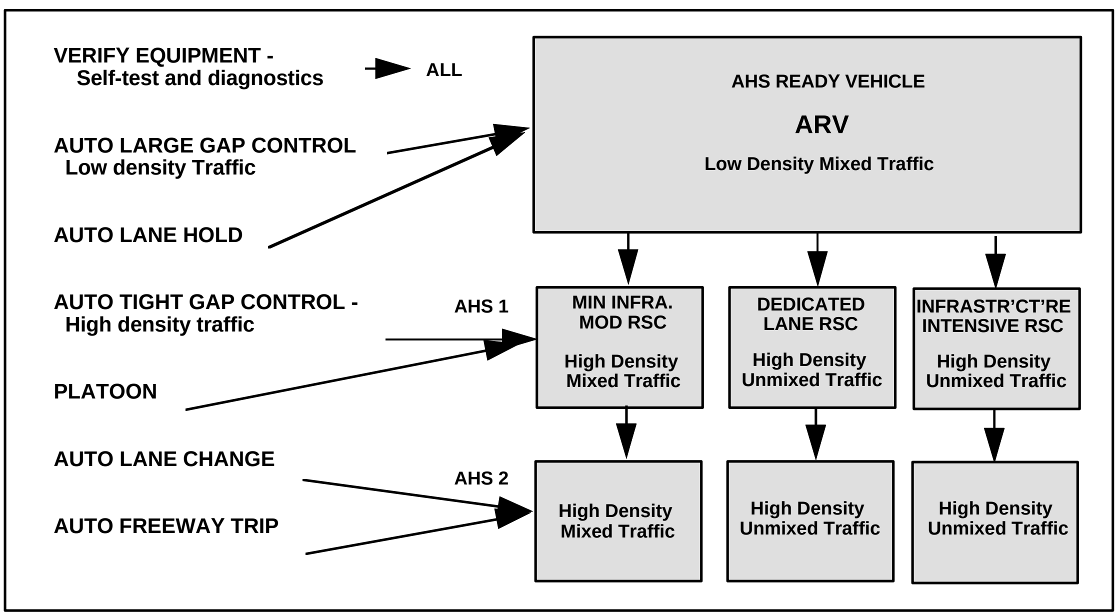

Figure I - 2. Functions and Evolutionary Phases

Step 3: Define the Physical Mechanization for each evolutionary step in each RSC.

This identifies the individual elements to be costed, and broadly identifies their major performance requirements. This can only be done by hypothesizing a system architecture, mechanization, and specific equipments for each of the RSCs in each of the evolutionary steps described: one cannot cost abstractions.

As already noted, the ARV stage is common to all three RSCs, but AHS1 and AHS2 are mechanized differently under the different RSCs. We identify the differences in enough detail to permit estimation of the cost impact of those differences.

Clearly there are alternative ways that the various functions can be mechanized, producing potentially different sets of physical elements. Where possible we have noted some of these alternatives, and our rationale for the choices made.

Step 4: Estimation of Subsystem Costs

Based on the mechanization developed in Step 3, specific lists of the equipments required in each of the phases of evolution and under each RSC are developed. Costs are estimated for each of these items of equipment as follows.

The first step in costing is to develop a "base year" unit cost for each item listed above. This "base year" cost is the cost to produce the item today, or if not feasible today, at the appropriate future date. Base year cost estimates are based on direct analogy to existing equipment, or by indirect analogy using parametric cost models that allow estimates based on weight, size, technology, etc.

As a part of this step, we estimate the development costs and possible other requirements that might affect costs.

Given base year costs and development costs, we then use historically based production cost reduction curves, technology improvement projections, and other historical data to project to specific acquisition years and quantities.

Using the same general methodologies, we identify reliability and maintenance requirements, and develop the appropriate cost increments.

Section II: SUBSYSTEM DEFINITION

Here we describe each major system element: its function, its performance characteristics, and physical nature to the degree they can be foreseen at this stage of system maturity.

We reiterate and emphasize that the system elements chosen here are for costing purposes only. We are still separated from final choices and mechanizations by a vast sea of unperformed analysis, engineering, and testing. As system development proceeds in coming years, it would be surprising if many of these choices were not changed with a concomitant impact on costs.

We begin with the description of the first evolutionary step, the AHS Ready Vehicle (ARV). As noted, this step is common to all three RSCs.

Hypothesized System Mechanization - The AHS Ready Vehicle (ARV)

The physical elements that are required by the ARV include:

Sensors

- A Sensor(s) to measure the range to the vehicle ahead in one's lane. We assume any confusion with vehicles in adjacent lanes in curves always errs by reading the nearest vehicle, so that errors do not cause unsafe conditions.
- A sensor(s) to measure vehicle position relative to the lane for automatic lane keeping.
- Sensors to sense the internal condition of the various equipments to support self-test and diagnostics.

Intelligence/Memory

- Computing elements to interpret the sensor signals and determine the desired vehicle responses,
- Internal computing to carry out self-test and diagnostics.

Communication

- None is assumed.

Actuators

– Drive-by-wire system components,

Interfaces

– A driver control interface.

– A intelligence/command input interface to drive-by-wire actuators.

We envision that these elements will be physically packaged as three subsystems: A Sensor-Intelligence Subsystem, the Drive-by-Wire Subsystem, and the Driver Interface. The self-test and diagnostic elements will be built into each of these subsystems.

We discuss each of these in turn.

Sensor-Intelligence Subsystem

The sensors and computational elements that interpret them and determine the desired vehicle responses may be a part of the same physical package simply because the lines blur between these functions. In fact, it is quite possible that the sensing elements and some computational elements will reside on the same solid state chips. For costing purposes, however, "processing" is considered separately from "sensing".

For costing purposes we assume the ARV Sensor-Intelligence Unit consists of the following elements:

– One Mulitbeam Millimeterwave Radar capable of ranging to 300 ft. (See rationale for choice below.)

– Magnetic Field Sensor to track magnetic nails for lane keeping. (See rationale for choice below.)

– The physical unit to allow velocity input from the vehicle speedometer system (small).

– A processor providing the computational elements that interpret sensor outputs and calculate desired vehicle responses.

– Self-Test/Diagnosis Unit, including its own sensors and, probably, its own miniprocessor.

Figure II - 1 depicts a schematic of the ARV system.

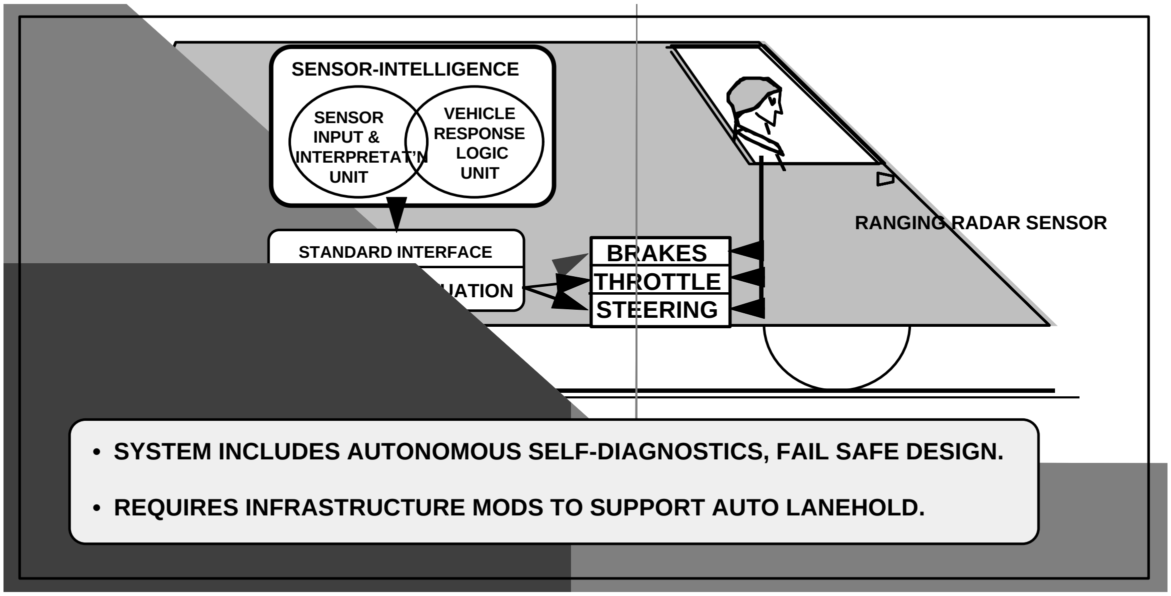

Figure II - 1 AHS Ready Vehicle (ARV)

The only special infrastructure requirements to support the ARV are the magnetic nails needed for lane tracking. Where these are not available, only the automatic longitudinal gap control feature can be activated.

The choice of radar as the means to measure range to the vehicle in front is largely because such systems are in operational use on Greyhound buses, and many are in development. Other approaches are being pursued, and it's quite possible that several alternatives will be put up for sale. Since one of the primary problems with developing an appropriate radar unit is one of cost, it probably represents the high end of possible range sensors.

Redundancy in range measurement is not suggested: we assume that the risk of collision caused by system failure is acceptably small because the allowable following distances are large.

The choice of magnetic nails to provide the lane keeping reference is based on the success of the PATH program using this approach, and its versatility to also serve as a device to transmit position fixes to the vehicle. The assumption that redundancy is not needed is more dubious, however, than in the case of range measurement. Certainly the system must be designed so that hard-over failures are precluded. If it is determined that redundancy is required - say a vision-based sensor to track lane marker lines - then consideration should be given to deleting the lane keeping feature from the ARV system.

For costing purposes we have assumed that only the single magnetic sensor will be acceptable.

The self-test and diagnostic feature will have to be designed integrally into all the elements of the system, but probably has its own control logic to cycle through tests, keep track of component behavior trends, etc.

Drive-by-wire Subsystem

This system consists of the following elements:

- A Brake Actuator
- A Throttle Actuator
- A Steering Actuator
- A Standard Interface Unit
- Sensors and computation to support self-test and diagnostics

We hypothesize that the input unit to the drive-by-wire actuators is a standardized interface unit keyed to the performance characteristics of the vehicle, and, like the actuators themselves, will be unique to the particular vehicle model, and would be built into the vehicle at the factory. It is expected that vehicles will be put in classes based on their braking, acceleration, and steering characteristics, and the vehicle's interface unit would convey this classification to the Sensor-Intelligence Subsystem; this would insure that the maneuvers called for under automated operation are within the capability of the vehicle to perform. (This will become increasingly important as the system is upgraded from the ARV level of performance to that needed for AHS1 and AHS2 operation.)

Further, a standardized interface permits a vehicle to accommodate Sensor-Intelligence units built by different manufacturers.

Brake, throttle and steering actuators are costed separately under two alternative assumptions. For the ARV these have been costed as the incremental cost of adding the drive-by-wire function while retaining essentially the current systems for manual control. This will almost surely be the approach taken with early systems before the reliability of drive-by-wire has been proven under operational conditions.

Once reliability has been established, however, it is likely that the drive-by-wire system will be used for both automatic and manual control with no mechanical back-up. This approach eliminates the current system connecting driver to brakes, steering, and throttle. There would have to be transducers of some sort to convert driver inputs (position movements of the steering wheel and the brake and throttle pedals) to electrical signals. These would be small, redundant, and high quality.

It is likely that cars will evolve toward the pure drive-by-wire system with or without AHS. Here we assume that all vehicles equipped for either AHS1 or AHS2 will use pure drive-by-wire, and our costs of AHS1 and 2 are based on this assumption. (Obviously those upgraded from ARV will still embody the dual systems.)

Driver Interface Unit

In the ARV this consists of the On-Off controls, and the necessary displays to convey system status to the driver. It may also contain a "slick street" switch actuated by the driver in the event of a degraded road surface: rain, snow, or icy spots. Or we may just recommend that the system be turned off in these conditions.

Hypothesized System Mechanization - The AHS1 System - Mixed Traffic, Minimum Infrastructure Modification RSC

The AHS1 system builds on the ARV system, but the nature of the changes is now dependent on the RSC chosen. We begin by examining the changes under the mixed traffic, Minimum Infrastructure Modification RSC.

AHS1 differs from the ARV system by adding the capability to operate at close following distances in heavy, mixed traffic. Lane-changing is still manual. The changes require the following kinds of upgrade from the ARV system:

- Because we want to minimize the following distance required for safety, there is a greater premium on a tight control loop: sensor detection and processing (sensor interpretation and vehicle response determination), and control actuation would desirably be closer to real time.

- We are more concerned with road conditions, because we are operating with tighter tolerances in determining safe following distance.

- The tactical driving scene is more complex: there is greater concern with the behavior of vehicles in adjacent lanes, and more information must be considered in processing. We will want maintain range tracking on the nearest vehicles in all three lanes, and read the turn signals of vehicles that could potentially enter the lane in front of us.

- We are much less tolerant of system failure or false alarms. This implies the need for redundant sensing, both in the forward quadrant and relative position for lane keeping.

We therefore have hypothesized the need for the following additions to the ARV system.

- We augment the ranging radar with a pair of Vision-based sensors to permit stereo ranging. Vision-based sensors also permit the reading of visible turn signals, and the tracking of the lane marker lines to provide an independent input for auto lane keeping and to allow positive segregation of vehicles by lane in the "scene".

- For costing purposes we will assume a rain/snow sensor on the vehicle modifies the allowable following distance in bad weather. There is also the possibility of measure road friction coefficient by observing deceleration response to braking; we are unsure of this technique because of the high noise level and spurious accelerations caused by deviations from the vertical - curable, but at higher cost.

- Increase the computational speed and memory requirements of the sensor processing unit.

- The Self-Test/Diagnosis Unit will be more complex.

- Assume that the drivers manual control system is eliminated, and manual control is now through the drive-by-wire system.

Road-to-vehicle Communication

We assume that we will want to relieve the driver of the need for any attention to the system during automated operation. This requires that we add road-to-vehicle communication for speed command inputs to the Sensor-Intelligence Subsystem.

(For costing purposes, the transmitter from the Traffic Management System (TMS) system is considered to part of the TMS system, since it will support other functions)

Platooning

In addition to the above changes, the introduction of the ability to operate in platoons requires the following:

- Platooning requires the addition of vehicle-to-vehicle communications between fore and aft vehicles. Range out to about 100 feet will be adequate, and the message content of frequent messages is low so the bandwidth requirements are moderate.

- The logic built into the Sensor-Intelligence unit requires expansion to cover the platoon/deplatoon decision and to control the new maneuvers involved.

- Some range sensor has to operate down to about 1 foot. This may be accomplished by tricks with the vision-based sensors (alternate optics, for example), or a new, dedicated sensor may be a preferred approach. For costing purposes, assume that the vision-type sensors are modified to measure down to one foot with 10% accuracy. This short range measurement is technically much simpler than the long range measurement.

In Appendix A we have attempted to get some measure of the on-board-vehicle processing power required to support the Sensor-Intelligence Subsystem. This has been done by decomposing the processor functions, and estimating the relative computing complexity of each of the individual tasks so identified. Given that the estimates made there are reasonably valid, the processing power required for the AHS1 operating in mixed traffic - the MIM RSC - is nearly seven times greater than is needed for the ARV.

Hypothesized System Mechanization - The AHS2 System - Mixed Traffic, Minimum Infrastructure Modification RSC

AHS2 adds the capability for automated lane changing, and thus introduces the possibility of the fully automated freeway trip from on-ramp to off-ramp.

AHS2 adds three new elements to AHS1. They are:

- The ability to do automated lane changes.
- The ability to accept the driver's input of a desired exit ramp.
- A protocol to select lanes and a method of navigating to the desired off-ramp at the end of the freeway trip.

Automatic lane change requires redundant or self checking sensors looking both directly to the side and back in the next lane to measure range and range rate of the nearest vehicle on the rear quarter - essentially 360^{o} coverage. We assume vision-type sensors for costing purposes. The Sensor-Intelligence Unit logic needs to be expanded to include this maneuver.

The navigation input can be either GPS, or messages embedded in the freeway. For example, a code using a combination of magnetic nails could identify each up-coming exit, or an RF beacon. The system could be preprogrammed to select the lane on the basis of trip distance. We assume for costing purposes that we either use the road-embedded message, or GPS that is already on-board to support other functions. There will be some slight modification to the Sensor-Intelligence Subsystem to accommodate this input.

The estimates of Appendix A indicate that the on-board Processor needs to be expanded from the AHS1 level by roughly 30 percent to handle automatic lane changing - the AHS2 level.

The schematic of the AHS2 MIM RSC vehicle is shown in Figure II - 2. The consistency with the ARV architecture is apparent, though many features have been added, and the capabilities increased substantially.

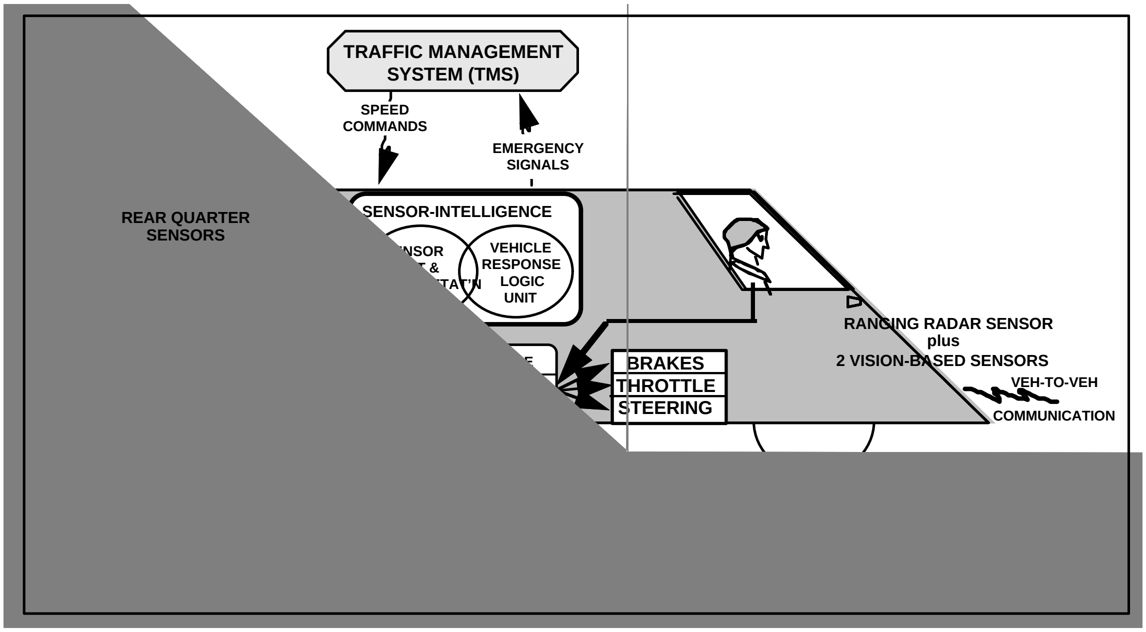

Figure II - 2. AHS2 Vehicle, MIM RSC, Operates in Mixed Traffic

Hypothesized System Mechanization - The AHS1 System - Dedicated Lanes (DL) RSC (the MIM RSC without mixed traffic)

We examine here how the provision of dedicated lanes, and therefore the removal of the need to operate in mixed traffic, might impact the AHS1 equipments.

Redundant Sensing - Still Needed, but Simpler

We conjecture that some supplement to the radar assumed for the ARV will be needed both to minimize the false alarms that will be more serious with the closer vehicle spacing, and that the probably choice will still be passive, vision-based sensing. The fact that all vehicles are equipped simplifies the second sensing system by eliminating the need for stereo ranging. For example, we can assume that each vehicle carries a distance measuring reference where it can be seen by the vehicle in back, say two emitters a fixed distance apart that can be seen by a vision-type ranging sensor. Thus a single vision-based sensor is adequate to provide the necessary redundancy.

Coping with Unequipped Vehicles Entering the Lane

Lanes separated by rumble strips

The law would largely eliminate the deliberate entry, but could not eliminate the accidental entry. The only response available to the AHS1 vehicle is braking, so the only useful capability is to be able to detect a large normal velocity component of vehicles in the next lane, whether it be a buffer lane or a lane of ordinary traffic. To either the radar or the vision-based sensor this appears as a rapid lateral movement of the object in the next lane. This processing is no different than that already implicitly assumed for the mixed traffic case.

Lanes separated by barriers with spaced openings for entry

Presumably barriers can reduce accidental lateral entry (and contain accidents in the AHS lane), but they pose new problems at the entry points. In ordinary lane changing in moderate to heavy traffic a driver wanting to change lanes is at least partially constrained to hold his speed to that of the lane traffic, and wait until a speed differential between the two lanes allows a gap to draw next to him. With the addition of a physical barrier between lanes, we have to also synchronize the availability of a gap with the barrier opening, which would seem to be a formidable additional complication into an already trying maneuver.

This synchronization problem could be simplified if the entering vehicle could command the vehicles already in the lane to create a gap at the proper instant, but this would require unique-to-a-particular vehicle communication that is probably not feasible without adding extensive infrastructure-based equipments; this would be inconsistent with this RSC. (This gap creation on demand is perfectly feasible in the Infrastructure Intensive RSC.)

Further, it may well be that the added dangers of barrier entry countervail the greater safety against rogue vehicles. Given that it is not clear that the safety trade-off favors the barrier system, and the vehicle entry-exit is made more difficult, we have assumed that the lanes will be separated by rumble strips.

Hypothesized System Mechanization - The AHS2 System - Dedicated Lanes (DL) RSC (the MIM RSC without mixed traffic)

We assume that the possibility of cooperation in the rearward sensor interpretation problem can reduce processing somewhat; otherwise the problem is the same as with the MIM system.

Net Impact: We conclude that the primary effect is due to the ability of vehicles to cooperate. The major effect is in the elimination of one of the vision-based sensors. Appendix A shows that eliminating mixed traffic operation cuts the processing power requirement by about 30 percent. The increment to add automatic lane changing is smaller absolutely, but at 35 percent is a larger percentage increase than in the MIM case.

Overall, the AHS2 processor for mixed traffic is roughly 45 percent larger than the AHS2 processor where dedicated lanes are available.

Figure II - 3 shows the schematic of the mechanization of the AHS2 DL RSC vehicle.

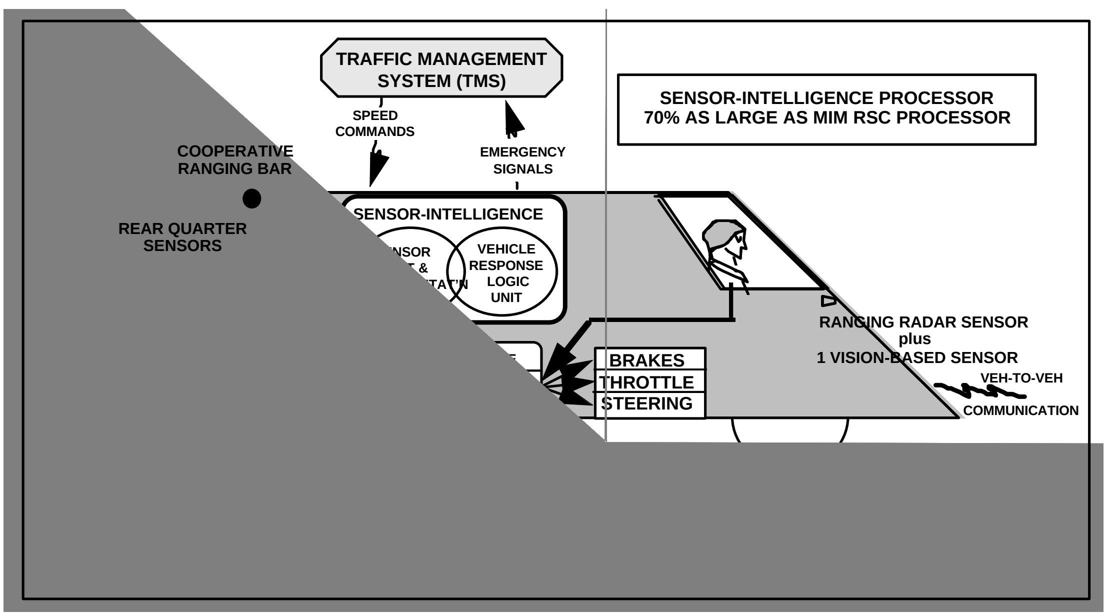

Figure II - 3 AHS2 Vehicle, Dedicated Lane RSC

Hypothesized System Mechanization - The AHS1 System - Infrastructure Intensive (II) RSC

In this RSC we assume a multilane facility with at least some of the lanes fully dedicated to automated vehicles. Unlike the DL RSC, which also has dedicated lanes, there are also major electronic functions added to the infrastructure.

We examine the possibility that some lanes, at least initially, will continue to be left to manual traffic. We assume that if there are manual lanes, the AHS vehicles will reach their lanes by traversing the manual lanes, or by special ramps that open directly into the AHS lanes. The two choices have different implications for vehicle electronics: these are described where pertinent.

There are two major mechanization options.

The first is to control all vehicle actions from the infrastructure; i.e., the infrastructure-based electronics makes both the decision to perform a given maneuver as well as executes that maneuver by directly commanding the vehicles' brake, throttle, and steering actuators. This option minimizes vehicle electronics .

The second is to assign to the infrastructure only the <u>decisions</u> to execute the speed changing, platooning/deplatooning, lane changing, and exiting maneuvers, and leave the actual <u>execution</u> of maneuvers - the brake, throttle, and steering actions - to vehicle-based sensors and computation.

We have selected the latter, even though it represents a much smaller departure from the MIM or DL scenario. On-board measurement of the tactical driving situation offers the best opportunity for tight-loop control, and probably the most accurate measurement of space between vehicles. It would be extremely difficult - perhaps impossible - to maintain the tight control loops needed for safe maneuvering using infrastructure based sensors to observe the scene, to process this data to identify relative motions, to then determine the desired vehicle response, and communicate back to each individual vehicle the brake, throttle and steering actions that vehicle needs to take.

Thus in our chosen mechanization the vehicle executes speed, platooning/deplatooning, lane changing, and exiting in response to commands from the infrastructure. On-board measurements govern the actual maneuvers. This is true for both the AHS1 and AHS2 capability levels.

Vehicle Electronics

As already noted, we assume pure Drive-by-Wire. There will be a need for Road-Vehicle Communication that is coded so that vehicle-unique messages can be sent. The changes required in the vehicle "brains", the Sensor-Intelligence Subsystem are described in the following. The Sensor-Intelligence Unit differs from that of the ARV system in the following ways.

- As with the MIM and DL RSCs, redundancy should be provided in range measurement. But with dedicated AHS lanes the alternative range measurement system can be simplified as already discussed under the Dedicated Lane RSC. We assumed that each vehicle carries a distance measuring reference where it can be seen by the vehicle in back, for example, two emitters a fixed distance apart that can be seen by a vision-type ranging sensor. This eliminates the need for stereo ranging, and simplifies both the sensor suite and the processing.

- This choice of on-board instrumentation implies that if manual lanes are to be traversed to reach the automated lanes, the ranging is derived from the radar only because the vision-based sensors cannot measure range on unequalled vehicles. We either accept the somewhat reduced fail-safety during this period, or require that the vehicle be under complete manual control during the traverse. To require redundant range measurement requires reverting to essentially the MIM vehicle electronics configuration, which we have not done. The alternate infrastructure option of special entry ramps to by-pass the manual traffic is functionally the near-equivalent of a totally dedicated facility.

- The Self-Test and Diagnostic Unit must have a receiver and transmitter to respond to the Auto Check-in Unit. This is an adjunct function of the basic receiver-transmitter unit.

- Because the behavior of traffic in the AHS lanes is predictable, and with manual traffic precluded from entering the AHS lanes, there is no need to read turn-signals, nor to measure range on any vehicles other than the one directly in front. This simplifies the processing, both the sensor interpretation and the desired vehicle response logic. (As noted above, this might be tempered if the MIM level of performance is considered to be required in order to traverse manual lanes under automated control.)

In addition to the above changes, the introduction of the ability to operate in platoons requires the same changes as in the MIM and DL RSCs:

- Platooning requires the addition of vehicle-to-vehicle communications between fore and aft vehicles. Range out to about 100 feet will be adequate, and the message content of frequent messages is low so the bandwidth requirements are low.

- The logic built into the Sensor-Intelligence unit requires expansion to cover the platoon/deplatoon decision and to control the new maneuvers involved.

- Some range sensor has to operate down to about 1 foot. Note that if we use the same technique of modifying the optics of the vision-based sensors of the MIM and DL RSCs, we give up redundancy in measurement because we now have only one forward looking sensor. We assume this to be acceptable.

The estimates of Appendix A show the AHS1 Sensor-Intelligence Unit processor to be only slightly smaller than that of the Dedicated Lane RSC; this is not surprising since the actual execution of vehicle maneuvers is essentially the same for both scenarios.

Infrastructure Electronics

The hypothesized operational concept is presented along with the descriptions of the individual system elements.

Automated Check-in Unit (ACU)

We assume the system operates as follows. A vehicle goes through rolling check-in on the on-ramp. The Check-in Unit on the ramp queries the self-diagnostic system on-board the vehicle, and assigns the vehicle a unique code to identify that vehicle to roadside sensors and road-to-vehicle communications. The vehicle, in turn, transmits the identification of the off-ramp it desires to the Master Control Center (MCC). The code is only good for the one trip, a new one is assigned each time the vehicle reenters the system.

The Check-in Unit consists of the following elements:

- Vehicle Condition Unit - We depend on self-diagnostics to actually check the systems; this just pulses it and asks is its OK.

- Code Assignment Unit - The ACU assigns the code to the vehicle that will be readable by the road side sensors, and identify communications to that vehicle.

There will be a Check-in Unit on every on-ramp.

Control Centers

In order to better fit the differing information requirements of the various control functions, we have defined two types of AHS Control Centers. There is one Master Control Center (MCC) that has purview over some fairly large length of freeway; for costing purposes we have assumed 50 miles.

We specify a larger number of Local Control Centers (LCCs) spaced at intervals along each freeway: for costing purposes we will assume every 5 miles on 4 lane freeways. The LCCs provide all direct commands to the vehicles, so in this sense the LCCs are the executive agents of the MCC. Their specific functions are described in detail in the following sections.

The primary information source to these control centers are sensors mounted along the freeway. These are the Vehicle Tracking Units. Their discussion is broken into two sections, the first dealing with information requirements, and the second with a description of the systems we have chosen for costing purposes.

Master Control Centers (MCC)

We have assigned to the MCC the two primary functions that require information from large segments of the freeway. The first is to oversee the routing and exiting of vehicles. The large coverage of the MCC increases the chances that the total trip of most freeway users is captured in one control center; this minimize the hand-off problem.

The MCC was informed of the desired off-ramp of each vehicle when the vehicle went through Automated Check-in. By periodic sampling (by the appropriate Vehicle tracking Unit) the MCC follows the progress of each vehicle through its freeway trip. When it time for some special action by that vehicle, the MCC alerts appropriate Local Control Center to watch for that vehicle and take the required action. By providing this service, the LCCs and the Vehicle Tracking Units are relieved of the task of continuously following every vehicle, and the volume of data transmitted from the VTUs and the processing by the LCC is markedly reduced. We have designed to manage-by-exception.

The MCC's second function is that of freeway congestion control. The MCCs directly control on-ramp metering, and coordinate this action as politically required with surface street Traffic Management. They also control (through the LCCs) vehicle speed and spacing, including platooning. An important implication of this second function is the ability to macro-manage vehicle flow when there are accidents and incidents.

Summarizing, the MCC includes the following subsystems:

- Vehicle Monitoring Unit - Receives from the Automated Check-in Unit the code and exit off-ramp (which may imply a transfer from one freeway to another, and so determines a route) for every entering vehicle. Receives periodic updates of vehicles position and velocity. Notifies each LCC that will have special commands for a particular vehicle - its code, ETA at that LCC, desired action (exit, switch to another freeway, lane change).

- Congestion Control Unit - Input is local freeway density and velocity from VTUs; accident/incident data, and ramp queues from Traffic Management

System; output is ramp-metering rates for the complete freeway under its control and commands to LCCs to adjust flow and vehicle spacing by exercising velocity control, degree of platooning, and lane loading in their segments.

- Operator Displays - Large displays of freeway flow status, accident/incident data, individual vehicle problems. But we assume that it is all automatic: human oversight is optional and episodic.

Local Control Centers (LCC)

The MCC alerts each LCC of the expected time of arrival of those vehicles that will require special attention or handling by that LCC. The LCC receives instructions from the MCC on desired actions for these individual vehicles, and acts as the executive agent to carry out these instructions. On the basis of this information the LCC alerts the appropriate Vehicle Tracking Units (addressed below) to provide data on these vehicles; there is no need to transmit the data on every vehicle that passes.

The LCC also executes all local zone commands: all changes in speed, degree of platooning, and lane loading. The LCC commands de-platooning to a particular vehicle when a vehicle needs out of a platoon in order to change lanes preparatory to going onto to another freeway or exiting at its selected ramp As discussed below, it can also order on a zone-by-zone basis some level of de-platooning when there is no longer a need for the degree of platooning that exists.

Summarizing, each LCC consists of the

- Individual Vehicle Control Unit - Receives from MCC codes on vehicles just entering its purview that will require action. Notifies specific sensor stations of vehicle codes it wants data on. The MCC tells it what actions need to be taken, and the LCC gives commands to execute them at the proper time.

- Zone Flow Control Unit - We assume that each zone is a roughly a half-mile length along the freeway. Broadcast commands to each zone are used to regulate stream speed, degree of platooning, and perhaps lane loading. (There are ways to have just a portion of vehicles respond to broadcast commands; for example, "all "D" vehicles in lane #3 change to lane #4 when possible".) These actions are responsive to commands from MCC Congestion Control and the LCC is little more than a communication channel: only minimal processing at the LCC is foreseen.

- Operator Displays - We have assumed that the LCCs are completely automated, but with displays to support oversight and equipment monitoring. The action is generally too fast to permit human intervention. There will be continuous recording of actions to allow playback. If there are major failures, then vehicles are switched to manual operation.

Vehicle Tracking Units - Requirements

The vehicle tracking units are the source of information to both the MCCs and the LCCs. Therefore the requirements for the system are dictated by the data needs of these Control Centers to carry out their function. We examine the information requirements for each of these functions individually.

Primary Information needs of the MCC

Congestion control - Congestion control, particularly in response to accidents or incidents, requires local-zone by local-zone regulation of stream flow and speed. The information needed to manage these actions is a knowledge of both incidents and of local flow conditions over large stretches of freeway - in theory to infinity. The stream speed and measurement of the gap between vehicles on each lane provide the basis for determining when velocity changes, platooning, or redistribution of traffic among lanes is needed.

The information is used to prevent local congestion, to increase lane flow potential, and to adjust flows to better cope with accidents and incidents. This information is also the basis for control of all ramp meters.

Congestion is prevented by keeping local vehicle densities below the critical level, and flow capacity is maximized by insuring that new vehicles can enter the lane as long as the density is below that level. Platooning is a powerful tool to increase the acceptable density, and thereby increasing capacity. Capacity is reached when the level of platooning is at its maximum in the dynamic balance between formation and separation, and the gaps between platoons are still too small to permit new entrants into the lane. They may be too small for safe lane changing or because the new entrant will reduce the gaps - even after local readjustments - to below the minimum safe gap for that speed and braking conditions. Since drivers only execute lane changes at the direction of the LCC, the LCC determines when this point is reached.

Without benefit of detailed analysis we judge that only moderate precision in this gap measurement is adequate - say 15 percent accuracy. While failure to platoon when needed could seriously impact lane capacity, it is not obvious that platooning too soon carries any significant penalty, and the system could always be biased to err in this direction.

It is not necessary to identify individual vehicles to accomplish this function, nor is complete coverage needed: we estimate that this function could be carried out satisfactorily with 50 percent coverage of the freeway surface.

The required actions are transmitted to the Zone Control Units of the LCCs for execution: we see no need to instruct particular vehicles to platoon.

Vehicle progress monitoring to establish a time-table for commanding actions - We assume that we will want to check a particular vehicle's progress at reasonable intervals throughout its trip, say every mile (until some action is due, then more frequently). We do not require 100 percent coverage; in fact, something like 20 percent coverage should be adequate for this function.

The data needed is the vehicle code, its absolute position, and its velocity. Precision in measurement of position is not required; velocity measurement accuracy trades with frequency of position checks needed.

Primary Information needs of the LCCs:

It is allocated to the infrastructure to command lane changes as a part of the routing and exiting function, and these commands are, of necessity, vehicle unique.

We leave it to the Congestion Control and Zone Control system to provide gaps for entry into the lane until capacity is reached - or to determine when maximum lane capacity has been reached.

We leave it to the driver to properly time the lane change maneuver. The driver waits for the gap into which he or she plans to enter, and selects the precise moment of the change just as he or she does today.

It is obviously crucial to keep lanes that must be traversed to permit exiting the freeway from reaching capacity.

Under these assumptions, the only function of the LCC with respect to lane change is to notify the driver of the need, and to carry out the MCC zone control functions.

AHS1 Summary of Information needs from the Vehicle Tracking Subsystem

We conclude that control at the AHS1 level of capability does not require particularly precise measurements of vehicle position and velocity. The data needed is essentially the same that is needed for good macro traffic management, with the proviso that we can identify individual vehicles for tracking purposes and to command specific maneuvers. Something like 50 percent coverage is probably adequate.

As will be discussed later, however, the move to the AHS2 level of capability with automated lane changing does impose new and more stringent accuracy requirements on the Tracking Unit sensors and sensor interpretation. This suggests that it may be imprudent to build an AHS1 system that is not capable of supporting AHS2 performance. Given the proper choice of sensors, the major difference between the two becomes scope of coverage: we assume for costing purposes 50 percent for AHS1 and 90 percent for AHS2.

The Vehicle Tracking Units - Description

We assume a Tracking Unit consists of a vision-type sensor and the interpretation subsystem with the capability to extract the vehicle code, the time, its position and velocity of every vehicle in its vision. (not all this data is transmitted, as already noted).

For costing purposes we have assumed that the vehicle transmits a binary identification code to the VTU through a strobe type light emitter mounted on the roof of the vehicle. The VTU detects the binary ID number and also correlates it with the specific vehicle image.

For purposes of costing, we assume a Tracking Unit on a 20 ft. pole every 150 ft. down the freeway; this gives a minimum grazing angle of 15^{o}, sufficient to see the road 30 ft. beyond an 8 ft. vertical. Each sensor will see each vehicle for at least 1.5 seconds.

The single unit should cover four lanes of traffic. Covering 150 feet along the freeway, it is doubtful that it sees more than 3 vehicles (or even fewer platoons) per lane at a time: a maximum total 12 vehicles or platoon units simultaneously.

We assume that we will need a sensor set for each direction of traffic.

This coverage implies some 35 units per mile for 100 percent coverage of traffic in one direction, 17 units/mile for AHS1 coverage, and 32 units/mile for AHS2 coverage. These numbers are doubled for both directions of traffic. If we assume the poles are center-mounted, then each pole can carry two tracking units, one for each direction.

Communication Subsystems

The following different communication data streams need to be accommodated. This may be accomplished through telephone, some form of broadcast, or dedicated hardwire. Several streams may share one subsystem. Figure II - 4 is offered to hopefully help clarify the following discussions.

Automated Check-in Units (ACUs) to MCC's Individual Vehicle Monitoring Unit (IVMU)

Very low data rate transmission of individual vehicle codes and desired exit off-ramps from every on-ramp.

Between Vehicle Tracking Units (VTUs) and MCC's Vehicle Monitoring Unit (VMU)

We assume the VMU updates progress on each vehicle every 60 sec, receiving code, position, and velocity data. The aggregate data received can be substantial, but the per VTU data is small. For example, assume a vehicle density of 80 vehicle/lane mile, 4 lanes, and 50 miles of freeway; this gives 16,000 reports per minute. But spread over some 20 per mile of VTUs - 1000 VTUs over the whole 50 miles - this is only 1 message every 4 seconds per VTU. If this rate is increased by a factor of 10 for the last mile of 10 mile average trips, we still get only 1 message every 2 sec per VTU. If, however, redundancy is provided by having, say, 4 VTUs respond to each data need, then the message rate could increase to about 2 messages per second. Not overwhelming.

We assume the MCC sends messages to specific VTUs to alert them to watch for Code X. The resulting message rate is the mirror image.

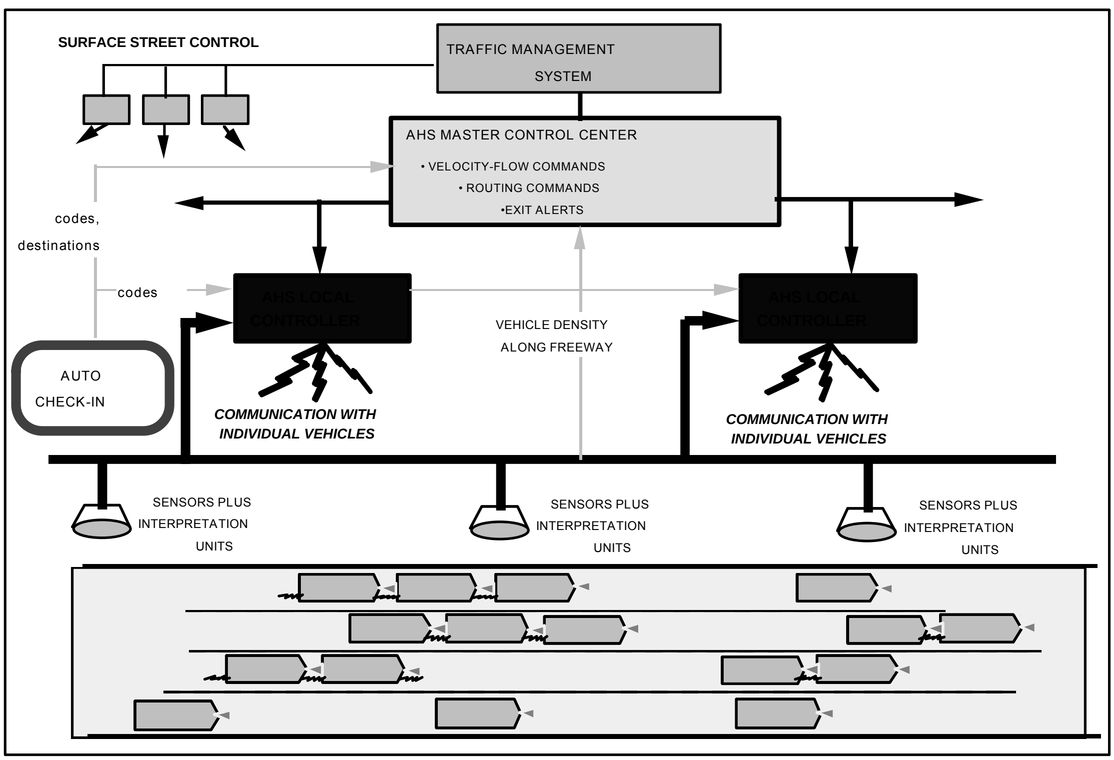

Figure II - 4. AHS2 Architecture Schematic, Infrastructure Intensive (II) RSC

Vehicle Tracking Units (VTUs) to MCC's Congestion Control Unit (CCU)

These messages are sent automatically, without request. We assume transmission of local vehicle density by lane, platooning status by lane, and stream velocity by lane measured at roughly 10 second intervals by, say, 3 or 4 VTUs per zone. Under our assumptions there are 20 VTUs per mile and 2 zones per mile, therefore 10 VTUs per zone. Thus we have one-third of VTUs firing every 10 seconds; on average this is one message per VTU every 30 seconds - a very low message rate.

MCC's Congestion Control Unit (CCU) to the LCC's Zone Flow Control Unit (IVCU)

Commands are by exception. Say 1 per minute per zone. Each LCC covers 10 half-mile zones: one message every 6 seconds for one direction of traffic, or 1 every 3 seconds total. In crisis (accident?) rate may increase slightly, but more probable that message content will rise more than the rate.

MCC's Vehicle Monitoring Unit (VMU) to the LCC's Individual Vehicle Control Unit (IVCU)

The MCC sends action commands - say 5 for a ten mile trip. This produces 1 action command every 2 minutes (at 60 mph) per vehicle, 8000 per minute for one direction of traffic, or 16,000 per minute for both directions. These 16,000/min are spread over 10 LCCs, giving nearly 30 actions/sec/LCC.

LCC's Zone Flow Control Unit (IVCU) to Vehicle Zones

These are broadcast messages to all the vehicles in a given zone. From above there is 1 message every 3 seconds to one of the 20 zones (both directions) under the purview of one LCC. This produces 1 message per minute per zone.

LCC's Individual Vehicle Control Unit (IVCU) to Vehicles

From above, each LCC handles nearly 30 actions per second. The only commands are platoon/deplatoon or lane change or exit. All only require one signal to one vehicle . Thus the net transmissions are 30 per second, and these are likely to be spread over distributed transmitters.

Hypothesized System Mechanization - The AHS2 System - Infrastructure Intensive (II) RSC

Vehicle electronics

We add the backward-looking sensors used in the MIM and DL RSCs to support lane changing, both to provide a back-up safety check when under infrastructure control, and to aid in lane changing while traversing the manual lanes in getting to and from the dedicated AHS lanes.

The same caveats expressed for AHS1 apply here. We continue to assume that we will operated without redundant range sensing during the short period while traversing the manual lanes. The difference is that the traverse is fully automated, including the lane changing directed by the LCC and executed by the vehicle.

Under these assumptions and based on the estimates of Appendix A, the AHS2 on-board processor is about a third larger than the AHS1 processor, but still only two-thirds the size of the AHS2 MIM RSC processor. Figure A - 1 (Appendix A) also shows that there would be very little change if the facility were totally dedicated, with no lanes allocated to manual traffic.

Figure II - 5 depicts the AHS2 Infrastructure Intensive Vehicle.

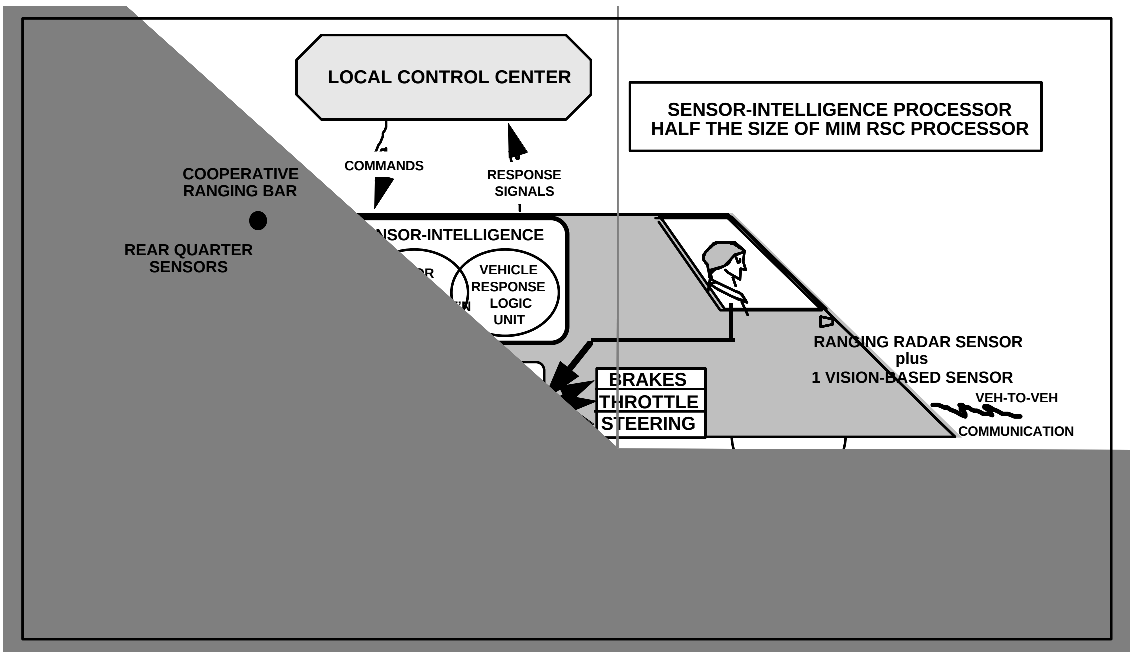

Figure II - 5. AHS2 Vehicle, Infrastructure Intensive (II) RSC, No mixed traffic

Infrastructure Electronics

Under AHS2 we can no longer leave the timing of the lane change maneuver to the driver. We discuss the implications:

We have the option of allocating to the vehicle the selection of the timing of the maneuver: this is the approach in the MIM AHS2. The other alternative is to assign the timing of the maneuver to the LCC, and leave only the execution of the maneuver to the vehicle. On the face of it, the former seems the most straight forward, but is at variance with the purpose of this study. We therefore examine LCC-directed lane changing.

The size gap needed for safe lane changing is a function of vehicle longitudinal performance, the relative stream velocity of the two lanes of traffic (which dictates the relative motion between the to-be-exited gap and the receiving gap), and the tolerances that must be included to account for inaccuracies in measurement and in timing.

If the relative velocity between lanes is kept to within 10 to 15 ft./sec, the gap required to accommodate manual lane change is probably around 40 feet. The minimum longitudinal safe gap is likely to be somewhat smaller, perhaps 30 or so feet. This implies that if we artificially maintain adequate lane change gaps then we penalize to some degree the maximum flow potential. The other option is to create gaps on demand.

We assume here that we will design for this capability: gap creation (or enlargement) on demand to accommodate automated lane changing.

Gap Creation on Demand

First, the LCC must select the vehicle in the receiving lane that is to be commanded to change velocity to create the gap. This requires an overview of the relative motion of some 6 to 8 vehicles in the two lanes. There is a penalty in holding the gap open longer than necessary - it decreases the number of gaps that can be created per unit time, and therefore the number of vehicles that can change lanes. There is also a penalty in creating a gap larger than is necessary - flow capacity is penalized because more space has to be maintained between all vehicles to absorb the momentary gap to keep such maneuvers from rippling through the whole traffic stream.

If the relative positions and velocities of the vehicles involved are calculated from absolute measurements on the individual vehicles - say from devices buried in the road - then the accuracy and timing requirements are stringent. For example, a 100 millisecond timing error in the observations on a vehicle can lead to a 10 ft. error in its absolute position. A 5 percent error in measuring each of their velocities can, with bad luck, produce an 10 ft./sec error in relative velocity that timing errors in initiation will translate into additional position errors.

These observations do not substitute for the more careful analysis the problem deserves if this option is to be given serious attention, but it does suggest that precision in measurement is more important than we have encountered thus far. Measurement accuracy - or inaccuracy - is a major driver of tolerances.

Since our concern is with positions and velocities relative to the maneuvering vehicle, it makes sense to measure these values directly, and not by deducing them from absolute measurements of all the individual vehicles involved.

The impact of having to traverse manual lanes

There is no special impact at the AHS1 level of capability; the maneuver is the same as with manual traffic today. With AHS2, however, the option of gap creation on demand is precluded, but the possible necessity is also reduced because now there will be gaps of various sizes, and some will be big enough to accommodate lane change. This us brings us back to our original mechanization option: to depend on the vehicle's backward-looking sensors to time the maneuver, or allocate it to the LCC. Aside from the possible need to require a somewhat larger gap than when all vehicles are under automatic control (to compensate for less predictable driver behavior), this is the same as the all-automated case.

Vehicle Tracking Units

Obviously this whole problem deserves far more analysis than is practical here, but, as noted, we conclude that sensors should be chosen to measure relative velocity and position directly. Such relative data is obtained if it is derived from the same frame of video or vision-based surveillance sensor.

Given the proper choice of sensors, the major difference between the AHS1 and AHS2 becomes the scope of coverage: we assume for costing purposes 50 percent for AHS1 and 90 percent for AHS2.

Communication Subsystems

LCC's Individual Vehicle Control Unit (IVCU) to Vehicles
From the discussion for AHS1, each LCC handles nearly 30 actions per second. Platoon/deplatoon commands, as in AHS1, require only one transmission to one vehicle; further coordination of the maneuver is handled between vehicles, using their vehicle-to-vehicle communication. For AHS2 we added gap creation on demand. Since two lanes are involved in a lane change, both the gap creation command and the change lanes command are sent from the LCC, which doubles the load. Assume 3 lane changes on average per trip; this increases the net transmissions from 30 to about 50 per second.

The LCC Processor

While the communications load may be reasonable, the processing load implied by AHS2 for the Individual Vehicle Control Unit (IVCU) in the LCC is substantial. Now the LCC must work the total kinematic problem for every lane change under its purview. This involves essentially continuous tracking of the involved vehicles for the duration of the gap creation maneuver (if needed) and timing the signal to the vehicle to initiate the actual lane change.

From the analysis of communication data loading under AHS1, we estimated that each LCC handles 30 actions involving individual vehicles per second. At least half of these are lane changes, which would imply the need to process a lane change maneuver 15 times per second. If each lane change requires, say, 5 seconds, then there are 60 such computations going on simultaneously. We make a horseback guess that it will require a factor of 5 or 10 increase in processor capability to handle AHS2.

Figure II - 6 presents an overall pictorial of the Infrastructure Intensive (II) RSC Dedicated Facilities.

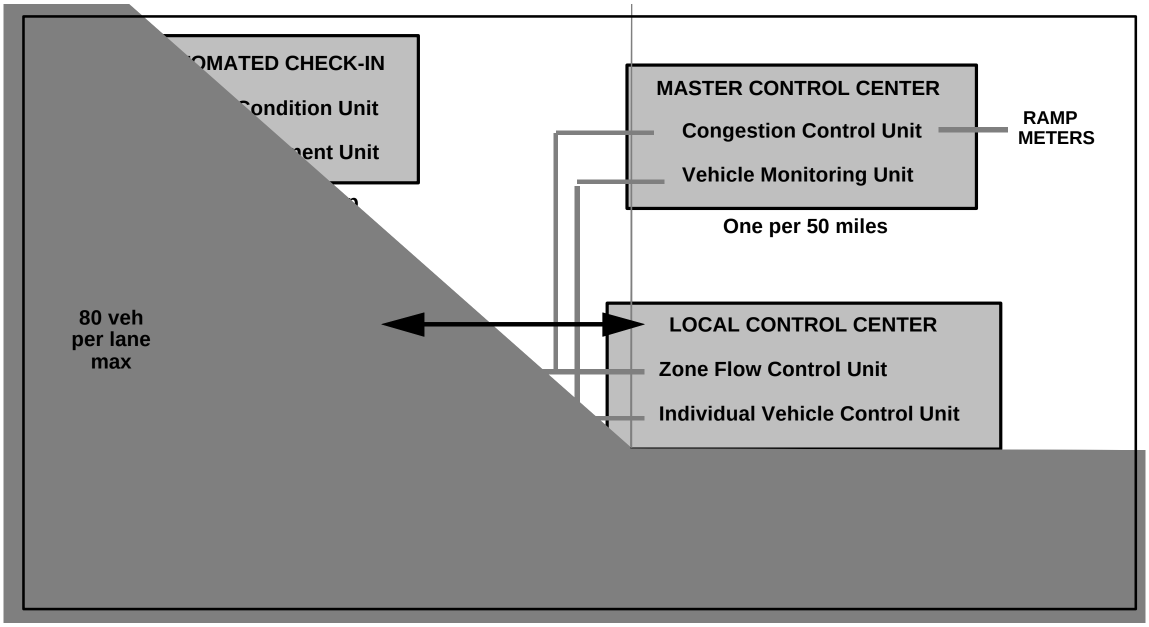

Figure II - 6 AHS2 Architecture, Infrastructure Intensive (II) RSC

Section III: PROJECTED ACQUISITION AND SUPPORT COSTS

Here we describe the projected acquisition and ownership costs for the equipments discussed in the preceding section. Costs include the initial cost of acquisition incurred by the owner plus expected maintenance costs over an assumed equipment life. Cost projections are included for each of the vehicle evolution and system configuration options previously identified. Software development and support costs are also included for owner specific software used in the infrastructure equipments.

The cost prediction model/methodology used and groundrules applied are detailed in Appendices B and C respectively. It should be especially noted that all cost values presented herein are in constant 1994 dollars. No account has been made for inflation or other time discounting of money.

It should also be noted that no specific development efforts have been identified and priced in this document. All hardware identified exists in some form today and developments for the specific AHS applications will occur as markets are identified. Similarly, vehicle and control center software will be developed through a natural sequence of development studies and market development.

Hardware Definition Matrix

The initial task in the cost estimating process, as described in Section 1 of this report, is to create a definitive list of representative equipment for each of the options to be costed. Tables III-1 and III-2 (vehicle and infrastructure electronics, respectively) are matrices consolidating the hardware previously described for each of the configuration options. Equipments are categorized by their function, i.e. Sensors, Intelligence, Communication, Actuators, and Interfaces. Applicability of a specific hardware element to a specific configuration option is shown by the quantity of that item in the configuration column. The same listings of equipment are used throughout the report when costs are described.

All of the equipments listed in Tables III-1 and III-2 exist in some application or stage of development today. The thrust of the costing effort described in this paper has been to establish current representative acquisition and support characteristics of each equipment and then forecast them into the future AHS application and time frame.

Predicted Acquisition Cost Summary

Vehicle electronics costs were predicted in the study for the seven configuration options, three acquisition years, and four production sizes for each year. Detailed listings of predicted costs for each of these cost options are contained in Appendices D and E. Table III-3 and Figure III-1 provide summaries of the predicted vehicle electronics acquisition costs. Table III-3 contains cost estimates by unit for each of the seven configurations. These costs are based on a 2002 procurement and a 1,000,000 unit production. Figure III-1 is a graphical representation of the total vehicle electronics cost for all vehicle options.

Table III - 1. AHS Vehicle Electronic Equipment Hardware Listing by Option

VEHICLE EQUIPMENT

NOMENCLATURE/ DESCRIPTION	Mixed Traffic			Dedicated Lanes				PURPOSE/FUNCTION
	Minimum Infrastructure Modification					Infrastructure Intensive		
	ARV low volume	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	
VEHICLE								
SENSORS								
MULTI BEAM MILLIMETER RADAR	1	1	1	1	1	1	1	Range to Vehicle Ahead
MAGNETIC FIELD SENSOR	1	1		1		1		Lane keeping
VISION-BASED SENSORS		2	4	1	3	1	3	Ranging, visible turn signals, tracking lane markers
RAIN/SNOW SENSOR		1	1	1	1			Detect wet road conditions
BEACON EMITTERS				2	2	3	3	Distance measuring reference, ID code transmission
MAG FILED SENSOR W/CODE			1		1		1	Lane keeping and location code reading
INTELLIGENCE								
PROCESSOR/DIAGNOSTICS (1)	1							Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (3.4)							1	Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (4.0)						1		Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (4.4)				1				Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (5.9)					1			Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (6.6)		1						Sensor data processing and diagnostics
PROCESSOR/DIAGNOSTICS (8.5)			1					Sensor data processing and diagnostics
COMMUNICATION								
ROAD TO VEHICLE (TMS), Receive		1	1	1	1			Speed Command inputs, delta to AM/FM radio
VEHICLE/VEHICLE, FORE & AFT		1	1	1	1	1	1	Platooning communication only, forward car to following car
R/T, AUTO CHECK-IN AND CONTROL						1	1	Vehicle to/from control communications, voice and digital
ACTUATORS								
BRAKE ACTUATOR	1	1	1	1	1	1	1	Automatic vehicle Control
THROTTLE ACTUATOR (Engine Control)	1	1	1	1	1	1	1	Automatic vehicle Control
STEERING ACTUATOR	1	1	1	1	1	1	1	Automatic vehicle Control
(LESS STD DIRECT DRIVE)		1	1	1	1	1	1	Removal of non drive-by-wire components
INTERFACES								
STD ACTUATOR INTERFACE UNIT	1	1	1	1	1	1	1	Standard interface, actuator/processor
DRIVER INTERFACE UNIT	1							On/off, status indicators
DRIVE BY WIRE DRIVER INT UNIT		1	1	1	1	1	1	On/off, status indicator, routing input, encoders on controls

Table III - 2. AHS Infrastructure Electronic Equipment Hardware Listing

INFRASTRUCTURE EQUIPMENT -- II RSC only

NOMENCLATURE/ DESCRIPTION	QUANTITY PER: MASTER CONTROL CENTER	LOCAL CONTROL CENTER AHS1	LOCAL CONTROL CENTER AHS2	ON RAMP	ROADWAY (per 100 MILES) AHS1	ROADWAY (per 100 MILES) AHS2	PURPOSE/FUNCTION
INFRASTRUCTURE							
SENSORS							
VISION-TYPE VEHICLE TRACKING UNIT (VTU)					3400	6400	Vehicle ID detection, velocity and spacing , location
INTELLIGENCE							
PROCESSOR, Vehicle Monitoring (VMU)	1						Oversees vehicle routing and exiting
PROCESSOR, Congestion Control (CCU)	1						Congestion Control
PROCESSOR, Individual Vehicle Control Unit (I (Basic)		1					Executes local zone commands, speed, platooning, etc.
PROCESSOR, Individual Vehicle Control Unit (I\ (Expanded)			1				Executes local zone commands, speed, platooning, lane change, etc.
PROCESSOR, Zone Flow Control Unit (ZFCU)		1	1				Zone broadcast control
COMMUNICATION							
AUTOMATED CHECK-IN UNIT (ACU)				1			Vehicle condition and code assignment
ACU MODEM				1			Land line communications
VMU MODEM	1						Land line communications
CCU MODEM	1						Land line communications
RECEIVER/TRANSMITTER, LCC - VEHICLE		1	1				Vehicle communications & control
IVCU MODEM		1	1				Land line communications
ZFCU MODEM		1	1				Land line communications
POWER							
LCC RACK POWER SUPPLIES		2	3				Processor and Modem Power
INTERFACES							
OPERATOR DISPLAYS	2						
OPERATOR KEYBOARDS	2						
PRINTER	1						
DISK DRIVES, etc.	Several						

Table III - 3. AHS Vehicle Electronic Equipment Cost Summary by Option

VEHICLE EQUIPMENT

Average Electronics Cost per Vehicle, 2002 procurement, 1994 dollars, 1,000,000 unit market

NOMENCLATURE/ DESCRIPTION	Mixed Traffic			Dedicated Lanes			
	Minimum Infrastructure Modification					Infrastructure Intensive	
	ARV, low volume	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change
VEHICLE	$ 1,397	$ 2,363	$ 2,796	$ 2,070	$ 2,453	$ 2,093	$ 2,209
SENSORS							
MULTI BEAM MILLIMETER RADAR	$ 306	$ 306	$ 306	$ 306	$ 306	$ 306	$ 306
MAGNETIC FIELD SENSOR	$ 60	$ 60	$ 0	$ 60	$ 0	$ 60	$ 0
VISION-BASED SENSORS	$ 0	$ 180	$ 360	$ 90	$ 270	$ 90	$ 270
RAIN/SNOW SENSOR	$ 0	$ 38	$ 38	$ 38	$ 38	$ 0	$ 0
BEACON EMITTERS	$ 0	$ 0	$ 0	$ 76	$ 76	$ 114	$ 114
MAG FILED SENSOR W/CODE	$ 0	$ 0	$ 72	$ 0	$ 72	$ 0	$ 72
INTELLIGENCE							
PROCESSOR/DIAGNOSTICS (1)	$ 103	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 534
PROCESSOR/DIAGNOSTICS (4.0)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 610	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	$ 0	$ 0	$ 0	$ 660	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	$ 0	$ 0	$ 0	$ 0	$ 851	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	$ 0	$ 939	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	$ 0	$ 0	$ 1,180	$ 0	$ 0	$ 0	$ 0
COMMUNICATION							
ROAD TO VEHICLE (TMS), Receive	$ 0	$ 10	$ 10	$ 10	$ 10	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	$ 0	$ 48	$ 48	$ 48	$ 48	$ 48	$ 48
R/T, AUTO CHECK-IN AND CONTROL	$ 0	$ 0	$ 0	$ 0	$ 0	$ 83	$ 83
ACTUATORS							
BRAKE ACTUATOR	$ 293	$ 293	$ 293	$ 293	$ 293	$ 293	$ 293
THROTTLE ACTUATOR (Engine Control)	$ 73	$ 73	$ 73	$ 73	$ 73	$ 73	$ 73
STEERING ACTUATOR	$ 468	$ 468	$ 468	$ 468	$ 468	$ 468	$ 468
(LESS STD DIRECT DRIVE)	$ 0	($ 234)	($ 234)	($ 234)	($ 234)	($ 234)	($ 234)
INTERFACES							
STD ACTUATOR INTERFACE UNIT	$ 6	$ 6	$ 6	$ 6	$ 6	$ 6	$ 6
DRIVER INTERFACE UNIT	$ 88	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	$ 0	$ 176	$ 176	$ 176	$ 176	$ 176	$ 176

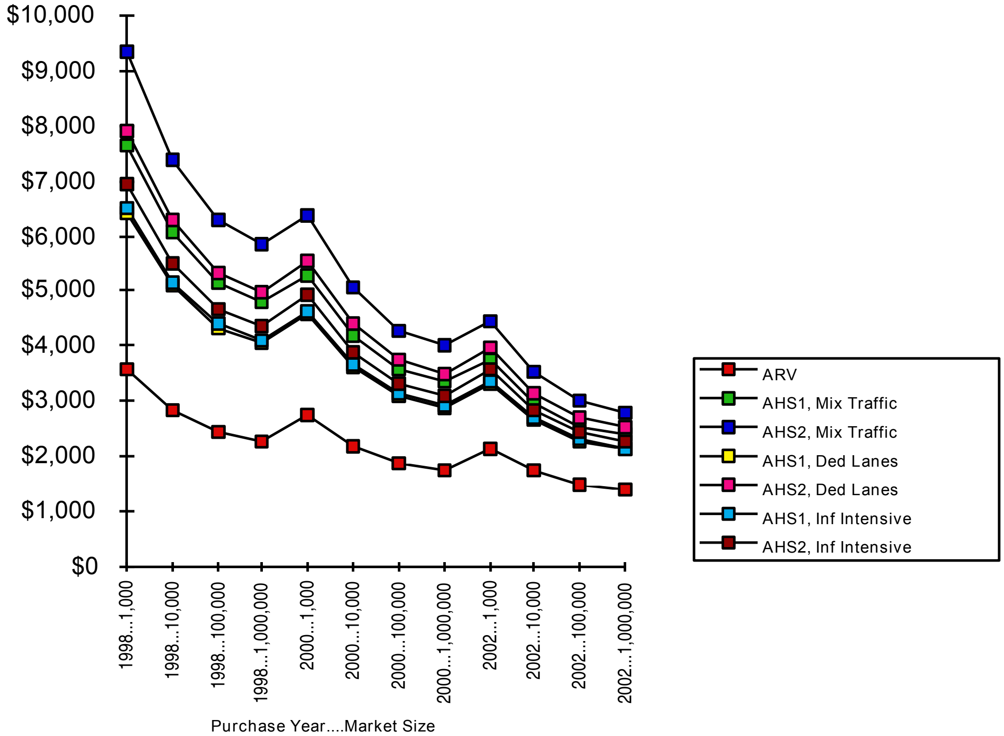

Figure III - 1. AHS Vehicle Electronic Cost, by Year and Market Size

Table III - 4 summarizes the infrastructure electronics costs for the Infrastructure Intensive RSC for acquisitions in each of the three procurement years. Costs in this table are for a 100 miles of roadway. This is assumed to include the following.

Item	Quantity per 100 miles
Master Control Centers	2
Local Control Centers	20
On Ramps	50

Table III - 4. AHS Infrastructure Electronic Equipment Cost Summary, II RSC

INFRASTRUCTURE EQUIPMENT -- II RSC only

COST PER 100 MILES OF ROADWAY 1994 Dollars

NOMENCLATURE/ DESCRIPTION	1998 ACQUISITIONS AHS1	1998 ACQUISITIONS AHS2	2000 ACQUISITIONS AHS1	2000 ACQUISITIONS AHS2	2002 ACQUISITIONS AHS1	2002 ACQUISITIONS AHS2
INFRASTRUCTURE	$493,096	$789,316	$316,942	$507,722	$202,518	$324,258
SENSORS						
VISION-TYPE VEHICLE TRACKING UNIT (VTU)	$ 306,000	$ 576,000	$ 197,200	$ 371,200	$ 125,800	$ 236,800
INTELLIGENCE						
PROCESSOR, Vehicle Monitoring (VMU)	$ 12,288	$ 12,288	$ 7,864	$ 7,864	$ 5,034	$ 5,034
PROCESSOR, Congestion Control (CCU)	$ 12,288	$ 12,288	$ 7,864	$ 7,864	$ 5,034	$ 5,034
PROCESSOR, Individual Vehicle Control Unit (IVCU) (Basic)	$ 73,720	$ 0	$ 47,180	$ 0	$ 30,200	$ 0
PROCESSOR, Individual Vehicle Control Unit (IVCU) (Expanded)	$ 0	$ 98,300	$ 0	$ 62,920	$ 0	$ 40,260
PROCESSOR, Zone Flow Control Unit (ZFCU)	$ 24,580	$ 24,580	$ 15,720	$ 15,720	$ 10,060	$ 10,060
COMMUNICATION						
AUTOMATED CHECK-IN UNIT (ACU)	$ 40,950	$ 40,950	$ 26,200	$ 26,200	$ 16,800	$ 16,800
ACU MODEM	$ 7,150	$ 7,150	$ 4,600	$ 4,600	$ 2,950	$ 2,950
VMU MODEM	$ 286	$ 286	$ 184	$ 184	$ 118	$ 118
CCU MODEM	$ 286	$ 286	$ 184	$ 184	$ 118	$ 118
RECEIVER/TRANSMITTER, LCC - VEHICLE	$ 5,320	$ 5,320	$ 3,400	$ 3,400	$ 2,180	$ 2,180
IVCU MODEM	$ 2,860	$ 2,860	$ 1,840	$ 1,840	$ 1,180	$ 1,180
ZFCU MODEM	$ 2,860	$ 2,860	$ 1,840	$ 1,840	$ 1,180	$ 1,180
POWER						
LCC RACK POWER SUPPLIES	$ 3,280	$ 4,920	$ 2,080	$ 3,120	$ 1,360	$ 2,040
INTERFACES						
OPERATOR DISPLAYS	Included in Processor Cost					
OPERATOR KEYBOARDS	Included in Processor Cost					
PRINTER	$ 1,228	$ 1,228	$ 786	$ 786	$ 504	$ 504
DISK DRIVES, etc.	Included in Processor Cost					

Predicted Control Center Software Development and Support Cost

Software is utilized throughout the AHS equipments. The vehicle equipment software is supplied to the owner as firmware and typically remains unchanged for the life of the equipment. The development cost of the software is amortized into the hardware sales price.

Control Center software takes two forms. Much of that software is hardware unique and supplied/priced the same as vehicle software. There is some control center software, however, which is developed and maintained specifically for the operations of the AHS system. The corresponding costs for this AHS unique software are generally a line item charged directly to the AHS system. Table III - 5 describes the software identified by this study, some cost determinate characteristics, and the predicted development and support costs.

The costs presented in Table III - 5 assume that much generic software development has occurred under separate studies and development contracts. The development costs shown reflect a situation where only the final ten percent new design and twenty percent new coding is required to finalize the software for a specific roadway/application.

The 20 year software support costs listed in Table III - 5, on the other hand, reflects the support cost for the total AHS unique software. These costs are not identifiable to a specific roadway distance and could apply to a hundred miles or a thousand miles or more depending upon the application of the software.

Table III - 5. AHS Control Center Software Characteristics and Cost Estimates

SOFTWARE NAME	RESIDES	FUNCTION	SLOC	APPL	DEVELOPMENT COST	20 YEAR SUPPORT COST
MCC VEHICLE MONITORING	VMU	Oversees routing and exiting Vehicle monitoring (via IVCU) Exit area notification & control	30,000	5	$715,800	$2,110,500
MCC CONGESTION CONTROL	CCU	Overall freeway congestion control On-ramp metering Speed, Spacing, and platooning Trafic Mgt System (TMS) cord.	20,000	5	$466,000	$1,389,400
LCC VEHICLE CONTROL, AHS1	IVCU	Executes local zone commands Speed/platooning changes VTU "Control"	10,000	5	$227,100	$613,300
LCC VEHICLE CONTROL , AHS2	IVCU	Executes local zone commands Speed/platooning changes VTU "Control" Lane Change control	35,000	8	$1,280,500	$4,344,300
LCC ZONE FLOW	ZFCU	Zone broadcast command control	5,000	4	$93,200	$276,500

Predicted Hardware Support Cost Summary

Hardware support costs are incurred because equipment failures will develop which must be fixed. To the vehicle owner, this means that his vehicle will have to be taken to a repair center and the failed item replaced. For the infrastructure owner/operator, failures mean that repair personnel must be dispatched to the failed equipment with the necessary items to effect the repair. Tables III - 6 and III - 7 summarize the projected costs, by item, expected to be generated by this repair activity.

Table III - 6 contains the vehicle support cost projections for each of the study hardware options based on a 1,000,000 unit procurement in 2002. Support costs are for the assumed average vehicle ownership period of 7 years.

Figure III - 2 is a graphical representation of a total vehicle electronics system support cost for all of the vehicle options.

Appendix E contains detailed charts showing the vehicle support cost projections by study option for each study pricing year/qty alternative.

Table III - 7 summarizes the infrastructure electronics support costs for a 20 year equipment life. Costs are shown for the infrastructure intensive RSC (RSC II) for both AHS1 and AHS2 .

Table III - 6. AHS Vehicle Electronic Equipment Support Cost Summary by Option

VEHICLE EQUIPMENT

Average Electronics 7 Year Support Cost per Vehicle, 2002 procurement, 1994 dollars, 1,000,000 unit market

	Mixed Traffic			Dedicated Lanes			
	Minimum Infrastructure Modification					Infrastructure Intensive	
NOMENCLATURE/ DESCRIPTION	ARV, low volume	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change
VEHICLE	$ 672	$ 1,732	$ 2,218	$ 1,300	$ 1,632	$ 1,259	$ 1,230
SENSORS							
MULTI BEAM MILLIMETER RADAR	$ 142	$ 142	$ 142	$ 142	$ 142	$ 142	$ 142
MAGNETIC FIELD SENSOR	$ 22	$ 22	$ 0	$ 22	$ 0	$ 22	$ 0
VISION-BASED SENSORS	$ 0	$ 56	$ 112	$ 28	$ 84	$ 28	$ 84
RAIN/SNOW SENSOR	$ 0	$ 1	$ 1	$ 1	$ 1	$ 0	$ 0
BEACON EMITTERS	$ 0	$ 0	$ 0	$ 4	$ 4	$ 6	$ 6
MAG FILED SENSOR W/CODE	$ 0	$ 0	$ 29	$ 0	$ 29	$ 0	$ 29
INTELLIGENCE							
PROCESSOR/DIAGNOSTICS (1)	$ 91	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 490
PROCESSOR/DIAGNOSTICS (4.0)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 582	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	$ 0	$ 0	$ 0	$ 646	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	$ 0	$ 0	$ 0	$ 0	$ 915	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	$ 0	$ 1,054	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	$ 0	$ 0	$ 1,477	$ 0	$ 0	$ 0	$ 0
COMMUNICATION							
ROAD TO VEHICLE (TMS), Receive	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	$ 0	$ 5	$ 5	$ 5	$ 5	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL	$ 0	$ 0	$ 0	$ 0	$ 0	$ 22	$ 22
ACTUATORS							
BRAKE ACTUATOR	$ 140	$ 140	$ 140	$ 140	$ 140	$ 140	$ 140
THROTTLE ACTUATOR (Engine Control)	$ 7	$ 7	$ 7	$ 7	$ 7	$ 7	$ 7
STEERING ACTUATOR	$ 265	$ 265	$ 265	$ 265	$ 265	$ 265	$ 265
(LESS STD DIRECT DRIVE)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES							
STD ACTUATOR INTERFACE UNIT	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4	$ 4
DRIVER INTERFACE UNIT	$ 1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	$ 0	$ 36	$ 36	$ 36	$ 36	$ 36	$ 36

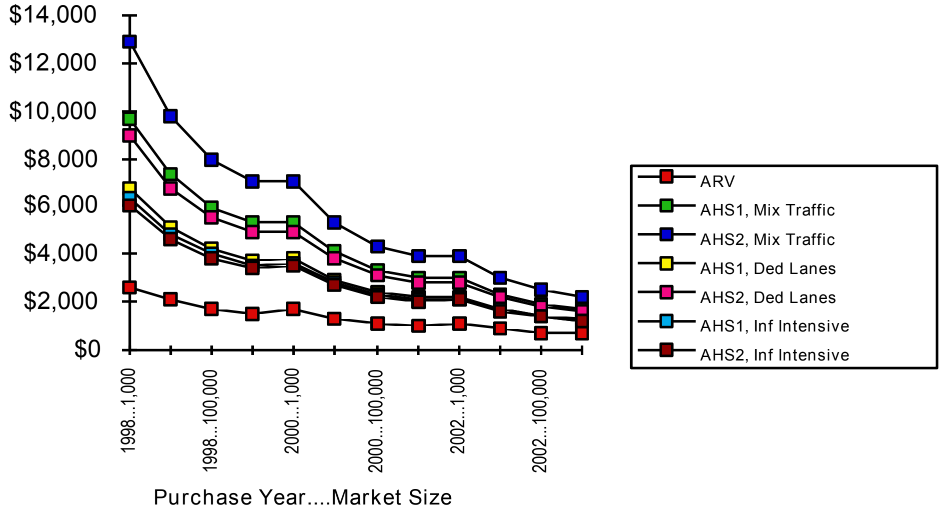

Figure III - 2. AHS Vehicle Electronic Support Cost, by Year and Market Size

Table III - 7. AHS Infrastructure Electronic Equipment Support Cost Summary, II RSC

ELECTRONICS 20 YEAR SUPPORT COST PER 100 MILES OF ROADWAY — 1994 Dollars

NOMENCLATURE/ DESCRIPTION	1998 ACQUISITIONS AHS1	1998 ACQUISITIONS AHS2	2000 ACQUISITIONS AHS1	2000 ACQUISITIONS AHS2	2002 ACQUISITIONS AHS1	2002 ACQUISITIONS AHS2
INFRASTRUCTURE	$2,328,992	$3,944,792	$1,260,256	$2,174,256	$1,085,256	$1,902,616
SENSORS						
VISION-TYPE VEHICLE TRACKING UNIT (VTU)	$ 1,618,400	$ 3,046,400	$ 945,200	$ 1,779,200	$ 867,000	$ 1,632,000
INTELLIGENCE						
PROCESSOR, Vehicle Monitoring (VMU)	$ 25,602	$ 25,602	$ 10,910	$ 10,910	$ 7,142	$ 7,142
PROCESSOR, Congestion Control (CCU)	$ 25,602	$ 25,602	$ 10,910	$ 10,910	$ 7,142	$ 7,142
PROCESSOR, Individual Vehicle Control Unit ((Basic)	$ 395,680	$ 0	$ 168,620	$ 0	$ 110,380	$ 0
PROCESSOR, Individual Vehicle Control Unit ((Expanded)	$ 0	$ 576,500	$ 0	$ 244,780	$ 0	$ 159,380
PROCESSOR, Zone Flow Control Unit (ZFCU)	$ 122,200	$ 122,200	$ 53,480	$ 53,480	$ 36,400	$ 36,400
COMMUNICATION						
AUTOMATED CHECK-IN UNIT (ACU)	$ 56,800	$ 56,800	$ 27,700	$ 27,700	$ 21,600	$ 21,600
ACU MODEM	$ 23,300	$ 23,300	$ 12,100	$ 12,100	$ 10,000	$ 10,000
VMU MODEM	$ 740	$ 740	$ 356	$ 356	$ 274	$ 274
CCU MODEM	$ 740	$ 740	$ 356	$ 356	$ 274	$ 274
RECEIVER/TRANSMITTER, LCC - VEHICLE	$ 24,060	$ 24,060	$ 11,660	$ 11,660	$ 9,000	$ 9,000
IVCU MODEM	$ 9,320	$ 9,320	$ 4,820	$ 4,820	$ 4,000	$ 4,000
ZFCU MODEM	$ 9,320	$ 9,320	$ 4,820	$ 4,820	$ 4,000	$ 4,000
POWER						
LCC RACK POWER SUPPLIES	$ 13,960	$ 20,940	$ 7,680	$ 11,520	$ 6,720	$ 10,080
INTERFACES						
OPERATOR DISPLAYS	Included in Processor Cost					
OPERATOR KEYBOARDS	Included in Processor Cost					
PRINTER	$ 3,268	$ 3,268	$ 1,644	$ 1,644	$ 1,324	$ 1,324
DISK DRIVES, etc.	Included in Processor Cost					

Base Unit Estimated Costs

All of the predicted costs in this study start with an estimate of the base unit price for each hardware item. This base price is the estimated value of what the unit (or a similar unit) costs today, typically in a small production quantity. These base cost values were generally derived by identifying catalog prices of similar items or through engineering experience. A parametric cost prediction model (PRICE) was used in two key areas where existing equivalent systems were not in production.

In all cases, consideration was given to the environment differences and prices adjusted accordingly.

The following paragraphs describe in more detail the source/rational used in the development of the base cost for the major items.

Multi-Beam Millimeter Radar The basis of this unit's predicted price is a developmental 77 MHz three-beam automotive radar currently in it's final stages of laboratory testing. The developmental model is built from existing components which are large and expensive. With some 77MHz component development, the design is expected to overcome many problems with other existing radar at a competitive price.

The base price used in this study was derived from the PRICE parametric model which predicts production cost based on a few key parametric input values. Most critical of these parameters are the forecast weight and technology for each of the expected production equipment subassemblies. Parameters describing the production version of the above radar were input to the PRICE model to obtain the base value used in this study.

Magnetic Field Sensor, with and without code reading capability. The cost estimating basis for this unit is production forecast information from people involved with magnetometer on current AHS test vehicles. The basis unit is a sensor only providing an analog output. Engineering judgment was used to increase the basis to add digital processing and then to further add the capability for interpreting position coding.

Vision Based Sensor A machine vision technology vehicle detection unit currently entering small scale production is the basis for the study projections for both the vehicle and highway application. The current unit includes sensor and processing to obtain real-time traffic flow data such as presence and velocity. Firmware can be changed to specify exact functions and windows (traps).

The PRICE model was also used to obtain the base cost of this unit. Adjustments were made in the input parameters to account for the increased capability requirements for the two applications of this study. Optics quality and processing capability of the vehicle unit were increased to provide the required accuracy for that application. Increased processing was also added to the roadway unit to add the ability to read ID codes transmitted from each passing vehicle.

Rain/Snow Sensor This sensor is a moisture detection device of some type, possibly as simple as a pair of probes. A nominal dollar value was selected.

Beacon Emitters These emitters are simple strobe lights. They are used in some applications as known distance references on the car ahead. They are also used for vehicle identification code transmittal.

Processor/Diagnostics Units Processors with a range of processing capabilities are specified in the paper (Appendix A describes the rational for ranking these capabilities). For pricing purposes the lowest capability was assumed to be equivalent to a current 486/66 motherboard with 32 Mb RAM. The upper end capability processor was assumed to be equivalent to two RISC Power PC VME board. Capabilities between were scaled according to the ranking developed in Appendix A, although it is recognized that in reality capabilities come in step functions not necessarily related to this processing capability.

Road to vehicle (TMS) receiver This RF receive capability is assumed to be provided as a minor modification to existing AM/FM radios. Engineering judgment was used to estimate the cost of this radio delta. In reality, a methodology could be used where no modification was even required.

Vehicle/Vehicle, Fore & Aft communications This equipment provides intra-platoon communication via a IR receiver in the front of each vehicle and a IR transmitter in the rear. Estimated base costs were developed from similar equipments currently in use for wireless computer LAN applications.

Receiver/Transmitter for Auto Check-in and Communications Existing packet format modem/transceivers list in the range of $600 to $1200. The lower end was used for the base estimate because of the low power requirements.

Actuators The author was unable to locate/talk to anyone with specific knowledge on digital brake, engine, and steering actuators. The base estimates used in the study were derived after discussions with a owner/operator of a local automobile repair business.

A smaller amount is included for the engine control actuator. It is assumed that our base automobile currently has a cruise control and computer controlled engine functions. The amount of modification required for full throttle control is not as significant as with the other actuators..

Interfaces Interface units include a digital interface for actuators and the physical interface with the vehicle driver. Engineering judgment was used for estimates in this area consistent with the general definition available for the units.

Infrastructure Processors The series of control center processors have been priced based on current catalog computers. Processors and their interface units (display, drives and keyboard) for the Master Control Centers are assumed to be equivalent to three of todays high-end PC with 20 inch displays.

Processors in the Local Control Centers are assumed to be card type units equivalent to todays VME card processors. Low capability processing was assumed to be equivalent to three 25Mhz 68040 VME card while the higher requirements were met with three each 66 and 100 Mhz VME modules.

Communication Modems All infrastructure communications were assumed to be by land wire with interfacing modems. The base price used in the study was derived from current catalog prices for plug-in 28.8 kbaud modems.

Local Control Center Power Supplies It is assumed that LCC equipment will require additional power development/condtioning. These units are in existence today in many forms. The study base price was derived as a typical catalog price today.

Section IV: PROJECTED VEHICLE UPGRADE COSTS

Here we describe the projected upgrade costs for an AHS Ready Vehicle (ARV). Referring back to the AHS evolution discussed in section I of this report, we understand that the ARV is an introductory vehicle. The ARV is capable of fully automated safe following and lane keeping on minimally modified existing facilities. This section discusses the costs involved for the owner who, subsequent to the purchase of an ARV, wishes to upgrade it to add the capabilities of one of the AHS/RCS equipment configurations defined in section II.

This section also presents cost projections for the vehicle owner who procures a AHS1 vehicle and desires to upgrade it to a AHS2 within the same RSC.

Upgrade Approach

There is a broad range of upgrade options which might exist for an ARV owner; and a corresponding wide range of expected upgrade costs. Two of the main factors from which the ARV owner may be able to select deals with the extent which the aerodynamics and aesthetics of the vehicle are maintained and what type of business organization performs the upgrade.

It is assumed at this point that the original ARV is not physically designed with mounting provisions integrated into the vehicle exterior body/finish for additional sensors . Obviously if the ARV owner wishes to have the required new sensors integrated into the vehicle design with no signs of paint differences, etc. he will most likely have to pay significantly for that. A less costly approach which some may accept would be sensors mounted on the bumpers and roof which are obviously add-ons.

The second choice which potentially has a big influence on cost is the business chosen to perform the modification. On one end of this spectrum might be low volume automobile dealerships who include such modifications as part of their normal maintenance department. Based on current business practices, this approach would use equipments from the dealership parts department with the attendant cost markups. Also little economies of scale and technician learning would be achieved.

The other possible end of the performing-organization spectrum could be a high-volume modification house specifically conceived for AHS upgrades. This organization would acquire parts directly from their original manufactures eliminating some cost markups. Some new parts might even be designed specifically for upgrade units. For example, instead of completely replacing the main processor, a supplemental processor might be added.

High volume AHS upgrade shops should also achieve greater economies of scale and learning improvements.

Combining these two issues; on the high cost end, the ARV owner could select a automobile dealership and require a "class" upgrade, with new sensors fully integrated into the vehicle body. On the low end, the ARV owner could select an "upgrade house" and elect minimum body modifications. The costs presented in the next paragraph are somewhere in the middle of this range as described in that paragraph in more detail.

Predicted Upgrade Cost Summary

Estimated ARV upgrade costs presented in this section assume a minimum-body-modification approach performed by an automobile dealership. It assumes additional units are installed where they did not exist in the ARV design and upgrade units replace existing units where applicable. The installed units are drawn from the dealership parts inventory and, with one exception, they are the same part numbers as installed in original manufactured AHS1 and AHS2 vehicles. The one exception assumed is the Driver Interface unit. It is assumed that some minimum display/switch panel is designed for upgrades rather than adding a complete new Drive by Wire Driver Interface unit. Existing standard direct drive brake and steering components left in the ARV are maintained.

The minimum-body-modification approach assumed means that installation kits are used for mounting sensors on the vehicle bumpers and/or roof top without great concern for an integrated appearance. New cables are added as necessary and routed in the most expeditious manor.

The predicted ARV upgrade costs are summarized in Tables IV - 1 and IV - 2. These tables show the cost for upgrading an ARV to any one of the other six equipment options used in this report. The costs in Table IV -1 assume that the upgrade is performed in the year 2000 and overall, a 10,000 unit market exists. The costs in Table IV -2 assume that the upgrade is performed in the year 2002 and overall, a 1,000,000 unit market exists. Items shown with dollar values are those which are replaced/added for the modification. Modification costs of mounting, cabling, installation, and checkout are shown in the bottom section of the table.

Table IV - 3 contains the predicted costs for a AHS1 to AHS 2 upgrade under the same ground rules as Table IV - 2. The upgrade is assumed to be within the same RSC, however, the cost for upgrading within any one of the three RSCs is shown.

Table IV -1. ARV Upgrade Cost Summary, 2000 Procurement, 10,000 unit market

VEHICLE EQUIPMENT

Average ARV Electronics Upgrade Cost per Vehicle, 2000 procurement, 1994 dollars, 10,000 unit market

	Mixed Traffic	Dedicated Lanes				
	Minimum Infrastructure Modification				Infrastructure Intensive	
NOMENCLATURE/ DESCRIPTION	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change
VEHICLE	$3,235	$4,518	$2,581	$3,749	$2,745	$3,265
SENSORS						
MULTI BEAM MILLIMETER RADAR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAGNETIC FIELD SENSOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSORS	$ 408	$ 816	$ 204	$ 612	$ 204	$ 612
RAIN/SNOW SENSOR	$ 91	$ 91	$ 91	$ 91	$ 0	$ 0
BEACON EMITTERS	$ 0	$ 0	$ 182	$ 182	$ 273	$ 273
MAG FILED SENSOR W/CODE	$ 0	$ 164	$ 0	$ 164	$ 0	$ 164
INTELLIGENCE						
PROCESSOR/DIAGNOSTICS (1)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 1,210
PROCESSOR/DIAGNOSTICS (4.0)	$ 0	$ 0	$ 0	$ 0	$ 1,382	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	$ 0	$ 0	$ 1,497	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	$ 0	$ 0	$ 0	$ 1,928	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	$ 2,129	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	$ 0	$ 2,675	$ 0	$ 0	$ 0	$ 0
COMMUNICATION						
ROAD TO VEHICLE (TMS), Receive	$ 23	$ 23	$ 23	$ 23	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	$ 109	$ 109	$ 109	$ 109	$ 109	$ 109
R/T, AUTO CHECK-IN AND CONTROL	$ 0	$ 0	$ 0	$ 0	$ 189	$ 189
ACTUATORS						
BRAKE ACTUATOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
THROTTLE ACTUATOR (Engine Control)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
STEERING ACTUATOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
(LESS STD DIRECT DRIVE)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES						
STD ACTUATOR INTERFACE UNIT	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVER INTERFACE UNIT	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	$ 90	$ 90	$ 90	$ 90	$ 90	$ 90
MODIFICATION COSTS						
MOUNTING PROVISIONS	$ 130	$ 190	$ 120	$ 180	$ 145	$ 205
CABLING	$ 105	$ 150	$ 90	$ 135	$ 113	$ 113
INSTALLATION/CHECKOUT	$ 150	$ 210	$ 175	$ 235	$ 240	$ 300

Table IV -2. ARV Upgrade Cost Summary, 2002 Procurement, 1,000,000 unit market

VEHICLE EQUIPMENT

Average ARV Electronics Upgrade Cost per Vehicle, 2002 procurement, 1994 dollars, 1,000,000 unit market

	Mixed Traffic		Dedicated Lanes			
	Minimum Infrastructure Modification				Infrastructure Intensive	
NOMENCLATURE/ DESCRIPTION	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change	AHS1, lane keep	AHS2, lane change
VEHICLE	$1,839	$2,568	$1,551	$2,222	$1,689	$2,011
SENSORS						
MULTI BEAM MILLIMETER RADAR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAGNETIC FIELD SENSOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSORS	$ 206	$ 412	$ 103	$ 309	$ 103	$ 309
RAIN/SNOW SENSOR	$ 67	$ 67	$ 67	$ 67	$ 0	$ 0
BEACON EMITTERS	$ 0	$ 0	$ 134	$ 134	$ 201	$ 201
MAG FILED SENSOR W/CODE	$ 0	$ 83	$ 0	$ 83	$ 0	$ 83
INTELLIGENCE						
PROCESSOR/DIAGNOSTICS (1)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 610
PROCESSOR/DIAGNOSTICS (4.0)	$ 0	$ 0	$ 0	$ 0	$ 697	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	$ 0	$ 0	$ 755	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	$ 0	$ 0	$ 0	$ 972	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	$ 1,074	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	$ 0	$ 1,349	$ 0	$ 0	$ 0	$ 0
COMMUNICATION						
ROAD TO VEHICLE (TMS), Receive	$ 12	$ 12	$ 12	$ 12	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	$ 55	$ 55	$ 55	$ 55	$ 55	$ 55
R/T, AUTO CHECK-IN AND CONTROL	$ 0	$ 0	$ 0	$ 0	$ 95	$ 95
ACTUATORS						
BRAKE ACTUATOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
THROTTLE ACTUATOR (Engine Control)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
STEERING ACTUATOR	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
(LESS STD DIRECT DRIVE)	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES						
STD ACTUATOR INTERFACE UNIT	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVER INTERFACE UNIT	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	$ 40	$ 40	$ 40	$ 40	$ 40	$ 40
MODIFICATION COSTS						
MOUNTING PROVISIONS	$ 130	$ 190	$ 120	$ 180	$ 145	$ 205
CABLING	$ 105	$ 150	$ 90	$ 135	$ 113	$ 113
INSTALLATION/CHECKOUT	$ 150	$ 210	$ 175	$ 235	$ 240	$ 300

Table IV -3. AHS1 TO AHS2 Upgrade Cost Summary, 2002 Procurement, 1,000,000 unit market

VEHICLE EQUIPMENT

Average AHS1 to AHS2 Electronics Upgrade Cost per Vehicle, 2002 procurement, 1994 dollars, 1,000,000 unit market. Upgrade is within same RSC

NOMENCLATURE/ DESCRIPTION	Mixed Traffic	Dedicated Lanes	
	Minimum Infrastructure Modification		Infrastructure Intensive
VEHICLE	$1,863	$1,486	$1,124
SENSORS			
MULTI BEAM MILLIMETER RADAR	$ 0	$ 0	$ 0
MAGNETIC FIELD SENSOR	$ 0	$ 0	$ 0
VISION-BASED SENSORS	$ 206	$ 206	$ 206
RAIN/SNOW SENSOR	$ 0	$ 0	$ 0
BEACON EMITTERS	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE	$ 83	$ 83	$ 83
INTELLIGENCE			
PROCESSOR/DIAGNOSTICS (1)	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	$ 0	$ 0	$ 610
PROCESSOR/DIAGNOSTICS (4.0)	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	$ 0	$ 972	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	$ 1,349	$ 0	$ 0
COMMUNICATION			
ROAD TO VEHICLE (TMS), Receive	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	$ 0	$ 0	$ 0
R/T, AUTO CHECK-IN AND CONTROL	$ 0	$ 0	$ 0
ACTUATORS			
BRAKE ACTUATOR	$ 0	$ 0	$ 0
THROTTLE ACTUATOR (Engine Control)	$ 0	$ 0	$ 0
STEERING ACTUATOR	$ 0	$ 0	$ 0
(LESS STD DIRECT DRIVE)	$ 0	$ 0	$ 0
INTERFACES			
STD ACTUATOR INTERFACE UNIT	$ 0	$ 0	$ 0
DRIVER INTERFACE UNIT	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	$ 0	$ 0	$ 0
MODIFICATION COSTS			
MOUNTING PROVISIONS	$ 60	$ 60	$ 60
CABLING	$ 90	$ 90	$ 90
INSTALLATION/CHECKOUT	$ 75	$ 75	$ 75

REQUIREMENTS FOR ON-BOARD PROCESSING

Getting a reliable fix on the absolute processing requirements is beyond our capability at this stage of system maturity, so in the costing the processor is treated parametrically. We have, however, made a horseback estimate of the *relative* computing requirements of the various configurations.

In Figure A - 1 we have listed the primary computing tasks attendant to vehicle control, and assigned a value to represent our intuitive judgment of the relative computing power requirements to carry each of them out. We will briefly discuss the rationale behind some of the estimates shown.

The radar provides range, range-rate, and azimuth for each of the nearest objects in own and adjacent lanes from its own internal processing. It "tracks" these objects so that normally turns do not cause lane ambiguities. Relatively little further manipulation of its output is needed to provide a basis for estimating the desire vehicle control responses to its readings; we have assigned a "1".

We consider the magnetometer processing to be a bit more complex, and have assigned a "2".

The vision-based sensors require much more complex external processing. There are three primary tasks: (1), extract the "lines"; (2), interpret the lines; and (3) fuse or compare the data from the vision-based sensors to get stereo ranging and with the radar output to provide an amalgamated assessment of the tactical situation.

Extracting lines is done by analog computation directly on the sensing chip. As of now, and barring some more innovative approach, we would accomplish line interpretation by roughly emulating the approach used in target recognition. The process should be simpler than that faced by the military in that the background is reasonable predictable, as are the shapes of interest. The orientation of these objects is also predictable. Even so, it is our judgment that this is the most computationally intensive process in the system, and the speed with which it can be carried out is the limiting factor on the "tightness" of the drive-train control loop. We have assigned the scene extraction process (line interpretation) a complexity of "10", with an extra "2" to calculate lateral position from the lane lines in the scene. Using stereo ranging, the first two tasks would have to be done separately for each sensor, and the stereo ranging process integrated into the fusion process, now made more complex - but perhaps more reliable - but the fact that there are now three sensors to fuse, not two.

The fusion process itself with stereo ranging has also been assigned a "10"; this is reduced to a "6" if there is only one vision-based sensor - a situation that is discussed later.

Following similar reasoning, values for other tasks have been assigned as shown.

The Processor calculates desired vehicle responses in both steering and longitudinal axes based on the "scene" data provided. We judge these calculations, in general, to be less demanding than the sensor manipulation.

Self-diagnostics processing is assumed to be performed separately, probably by distributed mini-processors.

Using these various estimates, the relative processing power required for the various configurations is presented in Figure A - 1.

	RELATIVE REQ'M'NT	ARV	Min Mod RSC AHS1	Min Mod RSC AHS2	Ded Lane RSC AHS1	Ded Lane RSC AHS2	Infra Intens RSC AHS1	Infra Intens RSC AHS2
SENSOR INTERPRETATION								
Radar	1	1	1	1	1	1	1	1
Magnetometer	2	2	2	2	2	2	2	2
Vis-Based - Scene Interpret (each)	10		20	20	10	10	10	10
Vis-Based - Lat posit'n extract(each)	2		4	4	2	2	2	2
Stereo Ranging + Fusion w/ radar	10		10	10				
Coop Ranging + fusion w/ radar	6				6	6	6	6
Read turn signals (both)	1		1	1				
Rear sensors scene/ range (both)								
Mixed traffic	6			6				6
Unmixed traffic	4					4		
Nav input integration	1			1		1		1
VEHICLE RESPONSE DETERMINATION								
Longitudinal (low density)	2	2						
Lateral	3	3	3	3	3	3	3	3
Longitudinal (high density)	4		4	4	4	4	4	4
Platoon decision								
Mixed traffic	4		4	4				
Unmixed traffic	3				3	3		
Platoon maneuver	4		4	4	4	4	4	4
Lane change timing								
Mixed traffic	4			4				
Unmixed traffic	3					3		
Lane change maneuver	4			4		4		4
		8	53	68	35	47	32	43

Figure A - 1 Relative Processing Power Requirements - Vehicle On-board Processor

The highly tentative nature of estimates such as these at this early stage of system definition is illustrated by the wide divergence in judgments by people who are experts in the field. Figure A - 2 is included to show alternative estimates of processing power. The estimates shown in Figure A - 2 were made by Dr. Steven Shladover, the Technical Director of the PATH project. The major difference between the two estimates is in the processing power required by the ARV: Rockwell estimates some six times greater power than Dr. Shladover. For the other systems the differences are not nearly so significant, ranging roughly around a factor of two.

	RELATIVE REQ'M'NT	ARV	Min Mod RSC AHS1	Min Mod RSC AHS2	Ded Lane RSC AHS1	Ded Lane RSC AHS2	Infra Intens RSC AHS1	Infra Intens RSC AHS2
SENSOR INTERPRETATION								
Radar	1	1	1	1	1	1	1	1
Magnetometer	.1	.1	.1	.1	.1	.1	.1	.1
Vis-Based - Scene Interpret (each)	10		20	20	10	10	10	10
Vis-Based - Lat posit'n extract(each)	2		4	4	2	2	2	2
Stereo Ranging + Fusion w/ radar	10		10	10				
Coop Ranging + fusion w/ radar	.1				1	1	1	1
Read turn signals (both)	1		1	1				
Rear sensors scene/ range (both)								
Mixed traffic	6			6				6
Unmixed traffic	1					4		
Nav input integration	1			1		1		1
VEHICLE RESPONSE DETERMINATION								
Longitudinal (low density)	.1	.1						
Lateral	.1	.1	.1	.1	.1	.1	.1	.1
Longitudinal (high density)	.1		.1	.1	.1	.1	.1	.1
Platoon decision								
Mixed traffic	1		1	1				
Unmixed traffic	.1				1	1		
Platoon maneuver	1		1	1	1	1	1	1
Lane change timing								
Mixed traffic	1			1				
Unmixed traffic	.5					.5		
Lane change maneuver	.1			1		.1		.1
		1.3	38.3	46.4	15.4	18	15.3	15.4

Figure A - 2 Alternative Relative Processing Power Requirements - Vehicle On-board Processor

COST PROJECTION METHODOLOGY AND MODEL

The objective of a cost prediction model is to simulate the real world factors that are expected to determine the future cost of a product, and by so doing provide an analytical means for the prediction of future costs. This appendix describes the model/methodology used to predict the AHS equipment acquisition costs presented in the body of the paper. Similar methodology was also used to predict maintenance requirements and costs.

In reality, the sales price paid for any particular item is determined by many factors, some rational and some not. The more obvious factors include the cost of producing the item, the cost of selling the item, the amount the purchaser is willing to pay, competitive alternatives, and how bad the seller wants to sell. The cost of producing the item typically decreases as production quantities increase. The cost of producing the item also typically decreases with time as new technologies are developed and applied. Further, new technologies and time allow for the addition of better features. Thus the product purchased today is typically more functional than a similar item bought in the past.

The model used in this study is somewhat of a simplification; its purpose mainly being to provide a consistent consideration of production quantities and technology effects with time. Basically, the model extrapolates a current product cost to a future cost as a function of time and production quantities. The three main inputs to the model are 1) an estimate of the current cost of the item or similar item, 2) an estimate of the effect of time (technology improvements) on the product's cost, and 3) an estimate of the effect of larger production quantities on the product's cost. The following sub-sections describe each of these further.

Estimates of Current Costs

The methodology/rationale for current cost data used in this study are presented in the body of this document. See Section III, Base Unit Estimated Costs.

Estimates of the Time Effect on Cost

If one were to not consider inflation and the greater utility built into a product over time, generally the sales cost of consumable items decrease with time. This is true so long as a active competitive market is maintained and the supply generally is able to meet the demand. Electronics equipment have been a good example of this over the past two decades. Some examples researched for this paper include the following. The percentage data shown were calculated from specific dollar values quoted in the references. It should be noted that inflation has been removed from the cost figures cited based on average inflation indices. Changes in the product's utility have not been adjusted for, however.

Reference: Telephone interview with Airtouch Cellular employee...
Portable Cellular Telephones, 1989 to present, 25% per year
Mobile Cellular Telephones, 1989 to present, 22% per year

Reference: Cellular Business Magazine, November 1993 page 54
Cellular Telephones in general, 1988 to 1983, 27% per year

Reference: GPS World Receiver Survey, January 1992 and January 1994
Average cost of non-military land GPS receivers, 1992 to 1994, 13 % per year

Reference: Martin Marietta PRICE Systems case studies
Computer cost per "Million floating point operations per second(MFLOPS)"
1979 to 1985, 33% per year

Reference: Rockwell International Parametrics Studies, data from 1970 to 1985
Average price per transistor, Microprocessor chips, 25% per year
Average price per bit, Memory chips, 40% per year

Based on the above data, the cost projections in this paper for electronic products assumed cost savings from technology improvements and other time factors to be 20 % per year. Electro mechanical items such as actuators historically have not exhibited as great of cost reductions They were assumed to have a 5 % per year cost savings. Again, it should be noted that net cost reductions occur only when there is an active competitive market. The model assumes this condition to apply from today forward.

Estimates of the Production Quantity Effect on Cost

Cost reduction curves are often applied to a given production process to account for the efficiencies and learning achieved from larger production quantities. Learning mainly applies to human processes. Greater efficiencies of large lots come from the application of machines.

Composite cost reduction curves accounting for both factors were used in the cost prediction model of this study. Based on experience the following values were selected. Standard industry cost reduction tables were used wherein the average unit cost for all items produced is reduced by the complement (1 - CRC %) of the amount shown every time the production quantity doubles. For example, for a 90 % CRC, the average unit cost of 2 units is 0.9 times the first unit and the average unit cost of 4 units is 0.81 (0.9 * 0.9).

The CRC values used in this sturdy are as follows.

Production Quantity Delta	Cost Reduction Curve
100 to 1,000 units	90%
1,000 to 10,000 units	93%
10,000 to 100,000 units	95%
100,000 to 1,000,000 units	98%

Combined Effect of Time and Production Quantities

The composite effect of technology improvements with time and economies/learning with increased production sizes are shown in Figures B - 1 and B - 2. Figure B - 1 shows the composite model used in this paper for electronics equipment.

Technology improvements for non-electronic equipment such as actuators is expected to not be as great as it is with electronics. Figure B - 2 shows the model used in this paper for such equipment.

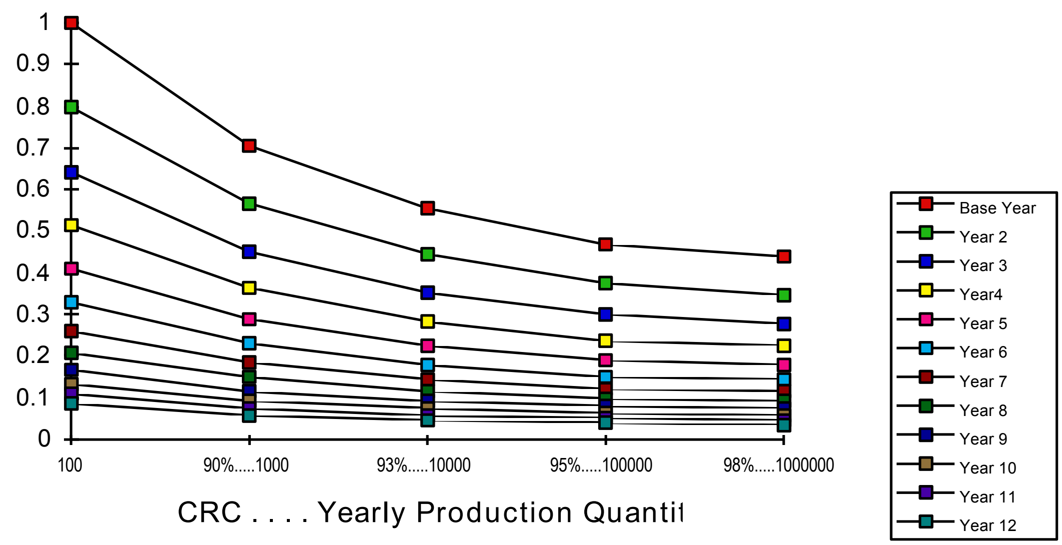

Figure B - 1. Electronic Equipment Cost Reduction Curves

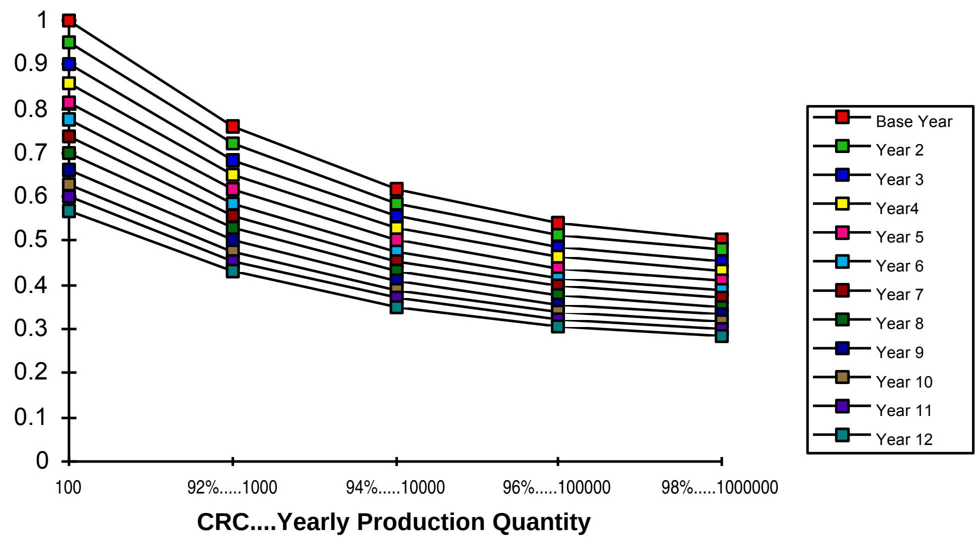

Figure B - 2. Mechanical Products Cost Reduction Curves

STUDY COST PREDICTION GROUND RULES

The ground rules which governed the development of the cost estimates presented are as follows.

1. All costs are presented in constant 1994 dollars, i.e. inflation is not considered.

2. Projected vehicle electronics costs will be on a per vehicle basis. Projected costs will be a function of the year of acquisition (1998, 2000, and 20002) and yearly market quantity (1,000, 10,000, 100,000, and 1,000,000). Predicted vehicle support costs will be for a period equal to the current average life of an automobile (7 years assumed).

3. Projected roadway electronics costs will be on an average per hundred miles basis. Costs will be a function of the year of acquisition. Predicted support costs will be for an arbitrary period of 20 years.

4. Vehicle operating costs will not be considered (fuel, etc.). Control Center operating costs; operators, utilities, etc. will also not be included

5. The Life Cycle Cost projections will not cover cost savings from possible benefits like higher highway capacity, reduced accidents, more efficient fuel consumption, no speeding tickets, etc.

6. Costs to establish maintenance support centers/systems will not be included. Study will assume manufacturer and other support resources will exist. Recurring maintenance actions will pay overhead to facility costs.

7. Vehicle manufacture markups, including installation costs, etc. are assumed to be 75%. Owner acquisition cost (installed) is equal to 1.75 times the equipment manufacturer's sales price. Replacement units for maintenance are marked up 100%.

8. No "Prime Contractor" markups are assumed for roadway electronics. Owner acquisition cost is the equipment manufacturer's sales price. Installation is costed separately.

9. For the AHS Ready Vehicle (ARV) Brake, throttle and steering actuators have been costed as the incremental cost to add the drive by wire function while retaining the current direct drive components. The AHS1 and AHS2 vehicles do not retain the manual control and the projected cost is the net cost with non-drive-by-wire elements deleted.

10. A Traffic Management System (TMS) is assumed independent of the AHS. No costs are included for its establishment or operation.

11. The cost of vehicle wiring for any of the AHS vehicles is not included, i.e. it is assumed to be approximately the same cost as a non-AHS vehicle.

12. Each AHS unit is assumed to include its own power supply/conditioning, i.e. power input to each is 12 volts DC.

13. Today's car is assumed as the base for the study.

VEHICLE ELECTRONIC ACQUISITION COST DETAIL CHARTS

The tables of this appendix detail the predicted vehicle electronics acquisition cost when purchased in a OEM vehicle. There is one table for each of the study electronics alternatives. Each table shows the predicted costs for each element of the vehicle electronics suite by acquisition year and production market size.

Table D - 1 AHS VEHICLE ELECTRONICS PURCHASE COST DETAIL
by year of purchase and production market size
AHS Ready Vehicle (ARV)

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 3,575	$ 2,858	$ 2,450	$ 2,291	$ 2,735	$ 2,193	$ 1,886	$ 1,763	$ 2,154	$ 1,732	$ 1,494	$ 1,397
SENSORS		$ 1,443	$ 1,134	$ 956	$ 894	$ 924	$ 726	$ 612	$ 572	$ 591	$ 465	$ 391	$ 366
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR	1	$ 238	$ 187	$ 157	$ 147	$ 152	$ 120	$ 101	$ 94	$ 97	$ 77	$ 64	$ 60
VISION-BASED SENSOR:		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 405	$ 318	$ 268	$ 251	$ 259	$ 204	$ 172	$ 160	$ 166	$ 130	$ 110	$ 103
PROCESSOR/DIAGNOSTICS (1)	1	$ 405	$ 318	$ 268	$ 251	$ 259	$ 204	$ 172	$ 160	$ 166	$ 130	$ 110	$ 103
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,540	$ 1,254	$ 1,095	$ 1,024	$ 1,390	$ 1,131	$ 988	$ 924	$ 1,254	$ 1,021	$ 892	$ 834
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 187	$ 152	$ 132	$ 123	$ 163	$ 132	$ 115	$ 107	$ 142	$ 116	$ 101	$ 94
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT	1	$ 162	$ 132	$ 115	$ 108	$ 146	$ 119	$ 104	$ 97	$ 132	$ 107	$ 94	$ 88
DRIVE BY WIRE DRIVER INT UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0

Table D -2 AHS VEHICLE ELECTRONICS PURCHASE COST DETA
by year of purchase and production market size
AHS1, Mixed Traffic, Minimum Infrastructure Modification

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 7,650	$ 6,057	$ 5,141	$ 4,807	$ 5,301	$ 4,205	$ 3,578	$ 3,345	$ 3,757	$ 2,988	$ 2,549	$ 2,384
SENSORS		$ 2,259	$ 1,779	$ 1,501	$ 1,404	$ 1,474	$ 1,162	$ 981	$ 917	$ 969	$ 764	$ 646	$ 604
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR	1	$ 238	$ 187	$ 157	$ 147	$ 152	$ 120	$ 101	$ 94	$ 97	$ 77	$ 64	$ 60
VISION-BASED SEN	2	$ 708	$ 557	$ 469	$ 438	$ 453	$ 356	$ 300	$ 281	$ 290	$ 228	$ 192	$ 180
RAIN/SNOW SENSOR	1	$ 108	$ 88	$ 77	$ 72	$ 98	$ 79	$ 69	$ 65	$ 88	$ 72	$ 63	$ 59
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 3,704	$ 2,911	$ 2,453	$ 2,293	$ 2,370	$ 1,863	$ 1,570	$ 1,468	$ 1,517	$ 1,192	$ 1,005	$ 939
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	1	$ 3,704	$ 2,911	$ 2,453	$ 2,293	$ 2,370	$ 1,863	$ 1,570	$ 1,468	$ 1,517	$ 1,192	$ 1,005	$ 939
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 230	$ 181	$ 152	$ 143	$ 147	$ 116	$ 98	$ 91	$ 94	$ 74	$ 62	$ 58
ROAD TO VEHICLE (TMS), Receive	1	$ 40	$ 32	$ 27	$ 25	$ 26	$ 20	$ 17	$ 16	$ 17	$ 13	$ 11	$ 10
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0

Table D - 3 AHS VEHICLE ELECTRONICS PURCHASE COST D

by year of purchase and production market size

AHS2, Mixed Traffic, Minimum Infrastructure Modification

	Qty per Vehicle	199				200				200			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 9,356	$ 7,398	$ 6,271	$ 5,864	$ 6,392	$ 5,064	$ 4,301	$ 4,021	$ 4,456	$ 3,538	$ 3,012	$ 2,816
SENSORS		$ 3,015	$ 2,373	$ 2,002	$ 1,872	$ 1,958	$ 1,542	$ 1,302	$ 1,217	$ 1,279	$ 1,008	$ 851	$ 796
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SEN	4	$ 1,416	$ 1,113	$ 938	$ 877	$ 906	$ 712	$ 600	$ 561	$ 580	$ 456	$ 384	$ 359
RAIN/SNOW SENSOR	1	$ 108	$ 88	$ 77	$ 72	$ 98	$ 79	$ 69	$ 65	$ 88	$ 72	$ 63	$ 59
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE	1	$ 286	$ 225	$ 189	$ 177	$ 183	$ 144	$ 121	$ 113	$ 117	$ 92	$ 78	$ 72
INTELLIGENCE		$ 4,653	$ 3,658	$ 3,082	$ 2,881	$ 2,978	$ 2,341	$ 1,972	$ 1,844	$ 1,906	$ 1,498	$ 1,262	$ 1,180
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	1	$ 4,653	$ 3,658	$ 3,082	$ 2,881	$ 2,978	$ 2,341	$ 1,972	$ 1,844	$ 1,906	$ 1,498	$ 1,262	$ 1,180
COMMUNICATION		$ 230	$ 181	$ 152	$ 143	$ 147	$ 116	$ 98	$ 91	$ 94	$ 74	$ 62	$ 58
ROAD TO VEHICLE (TMS), Receive	1	$ 40	$ 32	$ 27	$ 25	$ 26	$ 20	$ 17	$ 16	$ 17	$ 13	$ 11	$ 10
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176

Table D - 4 AHS VEHICLE ELECTRONICS PURCHASE COST DETA
by year of purchase and production market size
AHS1, Dedicated Lanes, Minimum Infrastructure Modification

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 6,413	$ 5,090	$ 4,332	$ 4,051	$ 4,565	$ 3,633	$ 3,100	$ 2,899	$ 3,338	$ 2,664	$ 2,280	$ 2,132
SENSORS		$ 2,121	$ 1,677	$ 1,421	$ 1,328	$ 1,443	$ 1,142	$ 970	$ 907	$ 1,000	$ 794	$ 675	$ 631
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR	1	$ 238	$ 187	$ 157	$ 147	$ 152	$ 120	$ 101	$ 94	$ 97	$ 77	$ 64	$ 60
VISION-BASED SEN	1	$ 354	$ 278	$ 234	$ 219	$ 227	$ 178	$ 150	$ 140	$ 145	$ 114	$ 96	$ 90
RAIN/SNOW SENSOR	1	$ 108	$ 88	$ 77	$ 72	$ 98	$ 79	$ 69	$ 65	$ 88	$ 72	$ 63	$ 59
BEACON EMITTERS	2	$ 216	$ 176	$ 154	$ 144	$ 195	$ 159	$ 139	$ 130	$ 176	$ 143	$ 125	$ 117
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 2,604	$ 2,047	$ 1,724	$ 1,612	$ 1,667	$ 1,310	$ 1,104	$ 1,032	$ 1,067	$ 838	$ 706	$ 660
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	1	$ 2,604	$ 2,047	$ 1,724	$ 1,612	$ 1,667	$ 1,310	$ 1,104	$ 1,032	$ 1,067	$ 838	$ 706	$ 660
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 230	$ 181	$ 152	$ 143	$ 147	$ 116	$ 98	$ 91	$ 94	$ 74	$ 62	$ 58
ROAD TO VEHICLE (TMS), Receive	1	$ 40	$ 32	$ 27	$ 25	$ 26	$ 20	$ 17	$ 16	$ 17	$ 13	$ 11	$ 10
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176

Table D - 5 AHS VEHICLE ELECTRONICS PURCHASE COST DETAIL

by year of purchase and production market size

AHS2, Dedicated Lanes, Minimum Infrastructure Modification

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 7,919	$ 6,274	$ 5,330	$ 4,983	$ 5,529	$ 4,390	$ 3,739	$ 3,496	$ 3,955	$ 3,149	$ 2,689	$ 2,514
SENSORS		$ 2,877	$ 2,271	$ 1,921	$ 1,797	$ 1,927	$ 1,523	$ 1,290	$ 1,206	$ 1,310	$ 1,037	$ 880	$ 823
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSO	3	$ 1,062	$ 835	$ 703	$ 658	$ 680	$ 534	$ 450	$ 421	$ 435	$ 342	$ 288	$ 269
RAIN/SNOW SENSOR	1	$ 108	$ 88	$ 77	$ 72	$ 98	$ 79	$ 69	$ 65	$ 88	$ 72	$ 63	$ 59
BEACON EMITTERS	2	$ 216	$ 176	$ 154	$ 144	$ 195	$ 159	$ 139	$ 130	$ 176	$ 143	$ 125	$ 117
MAG FILED SENSOR W/CODE	1	$ 286	$ 225	$ 189	$ 177	$ 183	$ 144	$ 121	$ 113	$ 117	$ 92	$ 78	$ 72
INTELLIGENCE		$ 3,354	$ 2,636	$ 2,221	$ 2,077	$ 2,146	$ 1,687	$ 1,421	$ 1,329	$ 1,374	$ 1,080	$ 910	$ 851
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	1	$ 3,354	$ 2,636	$ 2,221	$ 2,077	$ 2,146	$ 1,687	$ 1,421	$ 1,329	$ 1,374	$ 1,080	$ 910	$ 851
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 230	$ 181	$ 152	$ 143	$ 147	$ 116	$ 98	$ 91	$ 94	$ 74	$ 62	$ 58
ROAD TO VEHICLE (TMS), Receive	1	$ 40	$ 32	$ 27	$ 25	$ 26	$ 20	$ 17	$ 16	$ 17	$ 13	$ 11	$ 10
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176

Table D - 6 AHS VEHICLE ELECTRONICS PURCHASE COST DE

by year of purchase and production market size

AHS1. Dedicated lanes. Infrastructure Intensive

	Qty per Vehicle	1998 1,000	1998 10,000	1998 100,000	1998 1,000,000	2000 1,000	2000 10,000	2000 100,000	2000 1,000,000	2002 1,000	2002 10,000	2002 100,000	2002 1,000,000
VEHICLE		$ 6,501	$ 5,159	$ 4,391	$ 4,106	$ 4,622	$ 3,677	$ 3,138	$ 2,934	$ 3,374	$ 2,692	$ 2,304	$ 2,154
SENSORS		$ 2,121	$ 1,677	$ 1,421	$ 1,328	$ 1,443	$ 1,142	$ 970	$ 907	$ 1,000	$ 794	$ 675	$ 631
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR	1	$ 238	$ 187	$ 157	$ 147	$ 152	$ 120	$ 101	$ 94	$ 97	$ 77	$ 64	$ 60
VISION-BASED SEN	1	$ 354	$ 278	$ 234	$ 219	$ 227	$ 178	$ 150	$ 140	$ 145	$ 114	$ 96	$ 90
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	3	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 2,404	$ 1,890	$ 1,592	$ 1,489	$ 1,539	$ 1,209	$ 1,019	$ 953	$ 985	$ 774	$ 652	$ 610
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)	1	$ 2,404	$ 1,890	$ 1,592	$ 1,489	$ 1,539	$ 1,209	$ 1,019	$ 953	$ 985	$ 774	$ 652	$ 610
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 518	$ 408	$ 343	$ 321	$ 332	$ 261	$ 220	$ 205	$ 212	$ 167	$ 141	$ 131
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL	1	$ 329	$ 258	$ 218	$ 204	$ 210	$ 165	$ 139	$ 130	$ 135	$ 106	$ 89	$ 83
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176

Table D - 7 AHS VEHICLE ELECTRONICS PURCHASE COST DETAIL
by year of purchase and production market size
AHS2, Dedicated lanes, Infrastructure Intensive

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 6,957	$ 5,518	$ 4,693	$ 4,388	$ 4,914	$ 3,907	$ 3,331	$ 3,115	$ 3,561	$ 2,839	$ 2,428	$ 2,270
SENSORS		$ 2,877	$ 2,271	$ 1,921	$ 1,797	$ 1,927	$ 1,523	$ 1,290	$ 1,206	$ 1,310	$ 1,037	$ 880	$ 823
MULTI BEAM MILLIMETER RADAR	1	$ 1,205	$ 947	$ 798	$ 746	$ 771	$ 606	$ 511	$ 478	$ 494	$ 388	$ 327	$ 306
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSC	3	$ 1,062	$ 835	$ 703	$ 658	$ 680	$ 534	$ 450	$ 421	$ 435	$ 342	$ 288	$ 269
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	3	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176
MAG FILED SENSOR W/CODE	1	$ 286	$ 225	$ 189	$ 177	$ 183	$ 144	$ 121	$ 113	$ 117	$ 92	$ 78	$ 72
INTELLIGENCE		$ 2,104	$ 1,654	$ 1,393	$ 1,303	$ 1,347	$ 1,059	$ 892	$ 834	$ 862	$ 677	$ 571	$ 534
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	1	$ 2,104	$ 1,654	$ 1,393	$ 1,303	$ 1,347	$ 1,059	$ 892	$ 834	$ 862	$ 677	$ 571	$ 534
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 518	$ 408	$ 343	$ 321	$ 332	$ 261	$ 220	$ 205	$ 212	$ 167	$ 141	$ 131
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 190	$ 149	$ 126	$ 117	$ 121	$ 95	$ 80	$ 75	$ 78	$ 61	$ 51	$ 48
R/T, AUTO CHECK-IN AND CONTROL	1	$ 329	$ 258	$ 218	$ 204	$ 210	$ 165	$ 139	$ 130	$ 135	$ 106	$ 89	$ 83
ACTUATORS		$ 1,108	$ 902	$ 788	$ 736	$ 1,000	$ 814	$ 711	$ 665	$ 902	$ 735	$ 641	$ 600
BRAKE ACTUATOR	1	$ 540	$ 440	$ 384	$ 359	$ 488	$ 397	$ 347	$ 324	$ 440	$ 358	$ 313	$ 293
THROTTLE ACTUATOR (Engine Control)	1	$ 135	$ 110	$ 96	$ 90	$ 122	$ 99	$ 87	$ 81	$ 110	$ 90	$ 78	$ 73
STEERING ACTUATOR	1	$ 865	$ 704	$ 615	$ 575	$ 780	$ 635	$ 555	$ 519	$ 704	$ 573	$ 501	$ 468
(LESS STD DIRECT DRIVE)	1	($ 432)	($ 352)	($ 307)	($ 287)	($ 390)	($ 318)	($ 277)	($ 259)	($ 352)	($ 287)	($ 250)	($ 234)
INTERFACES		$ 350	$ 284	$ 247	$ 231	$ 309	$ 251	$ 219	$ 205	$ 274	$ 223	$ 195	$ 182
STD ACTUATOR INTERFACE UNIT	1	$ 25	$ 20	$ 17	$ 16	$ 16	$ 13	$ 11	$ 10	$ 10	$ 8	$ 7	$ 6
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 324	$ 264	$ 231	$ 216	$ 293	$ 238	$ 208	$ 195	$ 264	$ 215	$ 188	$ 176

VEHICLE ELECTRONIC 7 YEAR SUPPORT COST DETAIL CHARTS

The tables of this appendix detail the predicted vehicle electronics 7 year support cost. There is one table for each of the study electronics alternatives. Each table shows the predicted costs for each element of the vehicle electronics suite by acquisition year and production market size.

Table E - 1 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL

year of purchase and production market size

AHS Ready Vehicle (ARV)

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 2,650	$ 2,072	$ 1,728	$ 1,553	$ 1,671	$ 1,321	$ 1,112	$ 1,003	$ 1,091	$ 873	$ 741	$ 671
SENSORS		$ 995	$ 753	$ 610	$ 545	$ 531	$ 405	$ 330	$ 295	$ 287	$ 221	$ 182	$ 163
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR	1	$ 102	$ 80	$ 66	$ 60	$ 58	$ 46	$ 39	$ 35	$ 34	$ 28	$ 24	$ 22
VISION-BASED SEN		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 484	$ 372	$ 305	$ 274	$ 266	$ 207	$ 172	$ 155	$ 150	$ 119	$ 100	$ 91
PROCESSOR/DIAGNOSTICS (1)	1	$ 484	$ 372	$ 305	$ 274	$ 266	$ 207	$ 172	$ 155	$ 150	$ 119	$ 100	$ 91
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 12	$ 11	$ 10	$ 9	$ 9	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT	1	$ 2	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1	$ 1
DRIVE BY WIRE DRIVER INT UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0

Table E - 2 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL by year of purchase and production market size

AHS1, Mixed Traffic, Minimum Infrastructure Modification

	Qty per Vehicle	1998 1,000	1998 10,000	1998 100,000	1998 1,000,000	2000 1,000	2000 10,000	2000 100,000	2000 1,000,000	2002 1,000	2002 10,000	2002 100,000	2002 1,000,000
VEHICLE		$ 9,687	$ 7,350	$ 5,968	$ 5,326	$ 5,364	$ 4,097	$ 3,347	$ 2,993	$ 3,041	$ 2,344	$ 1,929	$ 1,730
SENSORS		$ 1,281	$ 974	$ 792	$ 708	$ 689	$ 529	$ 433	$ 389	$ 378	$ 293	$ 243	$ 219
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR	1	$ 102	$ 80	$ 66	$ 60	$ 58	$ 46	$ 39	$ 35	$ 34	$ 28	$ 24	$ 22
VISION-BASED SENSOR	2	$ 286	$ 221	$ 182	$ 163	$ 159	$ 124	$ 103	$ 93	$ 90	$ 72	$ 61	$ 55
RAIN/SNOW SENSOR	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 7,122	$ 5,337	$ 4,284	$ 3,811	$ 3,718	$ 2,792	$ 2,245	$ 1,998	$ 1,949	$ 1,468	$ 1,183	$ 1,054
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)	1	$ 7,122	$ 5,337	$ 4,284	$ 3,811	$ 3,718	$ 2,792	$ 2,245	$ 1,998	$ 1,949	$ 1,468	$ 1,183	$ 1,054
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
ROAD TO VEHICLE (TMS), Receive	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Table E - 3 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL by
year of purchase and production market size
AHS2, Mixed Traffic, Minimum Infrastructure Modification

	Qty per Vehicle	1998 1,000	1998 10,000	1998 100,000	1998 1,000,000	2000 1,000	2000 10,000	2000 100,000	2000 1,000,000	2002 1,000	2002 10,000	2002 100,000	2002 1,000,000
VEHICLE		$ 12,940	$ 9,789	$ 7,927	$ 7,069	$ 7,064	$ 5,376	$ 4,375	$ 3,909	$ 3,934	$ 3,017	$ 2,473	$ 2,214
SENSORS		$ 1,609	$ 1,226	$ 999	$ 894	$ 870	$ 670	$ 550	$ 494	$ 480	$ 375	$ 312	$ 281
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSORS	4	$ 573	$ 442	$ 363	$ 327	$ 317	$ 248	$ 206	$ 186	$ 181	$ 144	$ 122	$ 111
RAIN/SNOW SENSOR	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
MAG FILED SENSOR W/CODE	1	$ 143	$ 111	$ 92	$ 82	$ 80	$ 63	$ 53	$ 48	$ 46	$ 37	$ 32	$ 29
INTELLIGENCE		$ 10,047	$ 7,524	$ 6,036	$ 5,368	$ 5,238	$ 3,929	$ 3,156	$ 2,808	$ 2,740	$ 2,060	$ 1,658	$ 1,477
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)	1	$ 10,047	$ 7,524	$ 6,036	$ 5,368	$ 5,238	$ 3,929	$ 3,156	$ 2,808	$ 2,740	$ 2,060	$ 1,658	$ 1,477
COMMUNICATION		$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
ROAD TO VEHICLE (TMS), Receive	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Table E - 4 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL by year of purchase and production market size

AHS1, Dedicated Lanes, Minimum Infrastructure Modification

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 6,735	$ 5,140	$ 4,196	$ 3,750	$ 3,827	$ 2,946	$ 2,422	$ 2,170	$ 2,239	$ 1,742	$ 1,445	$ 1,299
SENSORS		$ 1,150	$ 874	$ 710	$ 634	$ 619	$ 474	$ 388	$ 348	$ 339	$ 263	$ 217	$ 196
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR	1	$ 102	$ 80	$ 66	$ 60	$ 58	$ 46	$ 39	$ 35	$ 34	$ 28	$ 24	$ 22
VISION-BASED SENSC	1	$ 143	$ 110	$ 91	$ 82	$ 79	$ 62	$ 52	$ 47	$ 45	$ 36	$ 30	$ 28
RAIN/SNOW SENSOR	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	2	$ 12	$ 10	$ 9	$ 8	$ 9	$ 8	$ 7	$ 6	$ 7	$ 6	$ 5	$ 5
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 4,301	$ 3,227	$ 2,594	$ 2,309	$ 2,252	$ 1,695	$ 1,365	$ 1,216	$ 1,186	$ 896	$ 724	$ 646
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)	1	$ 4,301	$ 3,227	$ 2,594	$ 2,309	$ 2,252	$ 1,695	$ 1,365	$ 1,216	$ 1,186	$ 896	$ 724	$ 646
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
ROAD TO VEHICLE (TMS), Receive	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Table E - 5 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL by year of purchase and production market size

AHS2, Dedicated Lanes, Minimum Infrastructure Modification

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 8,919	$ 6,781	$ 5,516	$ 4,925	$ 4,973	$ 3,809	$ 3,119	$ 2,791	$ 2,844	$ 2,200	$ 1,816	$ 1,630
SENSORS		$ 1,477	$ 1,126	$ 917	$ 821	$ 800	$ 615	$ 505	$ 454	$ 442	$ 345	$ 286	$ 258
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENSO	3	$ 430	$ 331	$ 273	$ 245	$ 238	$ 186	$ 155	$ 140	$ 135	$ 108	$ 91	$ 83
RAIN/SNOW SENSOR	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	2	$ 12	$ 10	$ 9	$ 8	$ 9	$ 8	$ 7	$ 6	$ 7	$ 6	$ 5	$ 5
MAG FILED SENSOR W/CODE	1	$ 143	$ 111	$ 92	$ 82	$ 80	$ 63	$ 53	$ 48	$ 46	$ 37	$ 32	$ 29
INTELLIGENCE		$ 6,158	$ 4,616	$ 3,707	$ 3,298	$ 3,218	$ 2,417	$ 1,945	$ 1,731	$ 1,689	$ 1,273	$ 1,027	$ 915
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)	1	$ 6,158	$ 4,616	$ 3,707	$ 3,298	$ 3,218	$ 2,417	$ 1,945	$ 1,731	$ 1,689	$ 1,273	$ 1,027	$ 915
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
ROAD TO VEHICLE (TMS), Receive	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Table E - 6 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL by
year of purchase and production market size
AHS1, Dedicated lanes, Infrastructure Intensive

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 6,384	$ 4,882	$ 3,992	$ 3,571	$ 3,652	$ 2,818	$ 2,322	$ 2,083	$ 2,153	$ 1,680	$ 1,398	$ 1,258
SENSORS		$ 1,156	$ 878	$ 714	$ 638	$ 623	$ 478	$ 391	$ 351	$ 343	$ 266	$ 220	$ 198
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR	1	$ 102	$ 80	$ 66	$ 60	$ 58	$ 46	$ 39	$ 35	$ 34	$ 28	$ 24	$ 22
VISION-BASED SENSOI	1	$ 143	$ 110	$ 91	$ 82	$ 79	$ 62	$ 52	$ 47	$ 45	$ 36	$ 30	$ 28
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	3	$ 18	$ 15	$ 13	$ 12	$ 13	$ 11	$ 10	$ 9	$ 10	$ 9	$ 8	$ 7
MAG FILED SENSOR W/CODE		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTELLIGENCE		$ 3,853	$ 2,893	$ 2,326	$ 2,070	$ 2,020	$ 1,521	$ 1,226	$ 1,092	$ 1,065	$ 805	$ 652	$ 582
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.0)	1	$ 3,853	$ 2,893	$ 2,326	$ 2,070	$ 2,020	$ 1,521	$ 1,226	$ 1,092	$ 1,065	$ 805	$ 652	$ 582
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 109	$ 87	$ 73	$ 67	$ 64	$ 52	$ 45	$ 41	$ 39	$ 33	$ 29	$ 26
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL	1	$ 91	$ 72	$ 61	$ 55	$ 53	$ 43	$ 37	$ 34	$ 32	$ 27	$ 23	$ 22
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Table E - 7 AHS VEHICLE ELECTRONICS SUPPORT COST DETAIL

year of purchase and production market size

AHS2, Dedicated lanes, Infrastructure Intensive

	Qty per Vehicle	1998				2000				2002			
		1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000	1,000	10,000	100,000	1,000,000
VEHICLE		$ 6,077	$ 4,661	$ 3,820	$ 3,419	$ 3,503	$ 2,713	$ 2,242	$ 2,013	$ 2,084	$ 1,633	$ 1,363	$ 1,228
SENSORS		$ 1,483	$ 1,131	$ 921	$ 824	$ 804	$ 619	$ 509	$ 457	$ 445	$ 348	$ 289	$ 261
MULTI BEAM MILLIMETER RADAR	1	$ 893	$ 674	$ 544	$ 485	$ 473	$ 359	$ 291	$ 260	$ 253	$ 194	$ 158	$ 142
MAGNETIC FIELD SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VISION-BASED SENS	3	$ 430	$ 331	$ 273	$ 245	$ 238	$ 186	$ 155	$ 140	$ 135	$ 108	$ 91	$ 83
RAIN/SNOW SENSOR		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
BEACON EMITTERS	3	$ 18	$ 15	$ 13	$ 12	$ 13	$ 11	$ 10	$ 9	$ 10	$ 9	$ 8	$ 7
MAG FILED SENSOR W/CODE	1	$ 143	$ 111	$ 92	$ 82	$ 80	$ 63	$ 53	$ 48	$ 46	$ 37	$ 32	$ 29
INTELLIGENCE		$ 3,220	$ 2,419	$ 1,946	$ 1,733	$ 1,690	$ 1,274	$ 1,028	$ 916	$ 893	$ 677	$ 548	$ 490
PROCESSOR/DIAGNOSTICS (1)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (3.4)	1	$ 3,220	$ 2,419	$ 1,946	$ 1,733	$ 1,690	$ 1,274	$ 1,028	$ 916	$ 893	$ 677	$ 548	$ 490
PROCESSOR/DIAGNOSTICS (4.0)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (4.4)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (5.9)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (6.6)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
PROCESSOR/DIAGNOSTICS (8.5)		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
COMMUNICATION		$ 109	$ 87	$ 73	$ 67	$ 64	$ 52	$ 45	$ 41	$ 39	$ 33	$ 29	$ 26
ROAD TO VEHICLE (TMS), Receive		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
VEHICLE/VEHICLE, FORE & AFT	1	$ 19	$ 15	$ 13	$ 12	$ 11	$ 9	$ 8	$ 7	$ 7	$ 6	$ 5	$ 5
R/T, AUTO CHECK-IN AND CONTROL	1	$ 91	$ 72	$ 61	$ 55	$ 53	$ 43	$ 37	$ 34	$ 32	$ 27	$ 23	$ 22
ACTUATORS		$ 1,160	$ 937	$ 803	$ 726	$ 866	$ 702	$ 603	$ 546	$ 647	$ 527	$ 454	$ 412
BRAKE ACTUATOR	1	$ 390	$ 316	$ 272	$ 246	$ 292	$ 237	$ 205	$ 185	$ 219	$ 179	$ 154	$ 140
THROTTLE ACTUATOR (Engine Control)	1	$ 16	$ 14	$ 12	$ 11	$ 13	$ 11	$ 10	$ 9	$ 10	$ 8	$ 7	$ 7
STEERING ACTUATOR	1	$ 753	$ 607	$ 519	$ 469	$ 561	$ 454	$ 389	$ 352	$ 419	$ 340	$ 292	$ 265
(LESS STD DIRECT DRIVE)	1	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
INTERFACES		$ 105	$ 87	$ 76	$ 69	$ 79	$ 66	$ 57	$ 52	$ 59	$ 50	$ 44	$ 40
STD ACTUATOR INTERFACE UNIT	1	$ 10	$ 9	$ 8	$ 8	$ 7	$ 7	$ 6	$ 6	$ 5	$ 5	$ 5	$ 4
DRIVER INTERFACE UNIT		$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0
DRIVE BY WIRE DRIVER INT UNIT	1	$ 95	$ 78	$ 68	$ 62	$ 71	$ 59	$ 51	$ 47	$ 54	$ 45	$ 39	$ 36

Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Roadway Costs

U.S. Department of Transportation
Federal Highway Administration
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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

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Preliminary Cost/Benefit Factors Analysis
Volume 4: Roadway Costs

1. Introduction

This report gives a preliminary cost benefit factor analysis for AHS implementation on a representative section of existing highway. The text describes the approach used to develop costs associated with the roadway portion of AHS and gives cost estimates for 5 basic implementation options described below.

2. Overview

A suggested general AHS implementation plan is:

• install 'transparent equipment in roadway' that will give perform to those vehicles equipped to 'see' it (e.g. magnetic nails)

• move towards separated roadway for AHS (rumble strips or paint, then fully separated with either continuous barriers with dedicated entry/exit ramps or separate facility such as an elevated structure

• expand AHS capabilities further so AHS traffic can now use existing roadways with other traffic and formerly dedicated facilities can be converted to higher speed through traffic.

However, the actual implementation will necessarily be a function of local roadway geometry, system demand, and a complex combination of other factors. Very few existing roadways can accommodate these specific conversions directly. Therefore, we have generated roadway retrofit options that can be used depending on local geometry to support this general evolution philosophy.

3. General Concepts

For the purposes of this discussion of cost estimates of retrofit options, the AHS guidance system is assumed to be the magnetic nail system. This is primarily because this system is further along in technological development than other guidance systems. With the magnetic nail system, the highway itself is passive. This system requires that all active electronics be mounted in the AHS vehicles. In retrofitting a conventional highway with the magnetic nail system the only “high tech” change is the addition of magnetic nails whose cost is negligible. Other cost items required to retrofit a conventional highway to AHS relate to infrastructure (bridges, new lanes, retaining walls etc) to create segregated AHS lanes. Some changes in geometrics may be required but they are similar to geometric revisions required for bus HOV lanes.

Infrastructure Considerations

Operational issues considered in this study include: separation of AHS vehicles from conventional vehicles, ramp capacity, facilities needed for verification of mechanical and electronic adequacy of AHS vehicles, general design considerations, and maintenance and life cycle costs. Where possible those issues were addressed directly. We noted those areas where further development is necessary before accurate costs can be developed.

Separation of AHS and Conventional Vehicles

A primary consideration is the concept of separation of AHS equipped vehicles from conventional vehicles. Based on good engineering practice, one method of separation is to use a concrete barrier between the AHS equipped and conventional vehicles. This method of separation works best when:

- weaving from the outside lanes to the inside lanes is not required for operation, and
- the concrete barrier is continuous for safety considerations.

Further, a continuous barrier would be required when there are dedicated entry/exit ramps for AHS vehicles. Note however, that when immediate access is required for rescue vehicles a continuous barrier would be a serious obstacle.

A discontinuous barrier might facilitate movement of AHS vehicles from the outside lanes to the AHS lanes inside. However, by good engineering practice a discontinuous traffic barrier should not be permitted since it would be a traffic hazard with potential high liability.

Bechtel's experience with worldwide highway installations suggests that when there is dissimilar traffic in adjacent lanes, there will be a certain amount of friction. For example, when the AHS lanes and conventional lanes are adjacent, AHS vehicles merging in and out of the AHS lane will cause some loss of capacity in the conventional lane. However if there is a buffer lane there will be less friction and a higher capacity for the conventional lane.

Ramp Capacity

For purpose of this study, ramp capacity is assumed to be adequate to support added AHS lanes. It is a consideration that will require further study at a later date. To determine ramp capacity with mixed flow one would require the AHS vehicle travel on the ramp at speeds comparable to non AHS vehicles. This requires that the vehicles are either pre-approved or inspected elsewhere, which could include vehicle testing at certified gas stations. Ramp capacity would be severely compromised if ramps were used to provide vehicle inspection for AHS adequacy. However if vehicle verification could be done while the vehicle is in motion, this could potentially alleviate the concern. More technology needs to be developed before the actual cost impact on ramp capacity can be evaluated.

In this study, dedicated separate access for AHS vehicles has been used for some retrofit options where required by the geometrics. Access would be from the middle of overcrossings with connecting ramps going to and from the AHS lane located in the middle of the freeway. This method was chosen as it is less expensive than access from the sides of the highway. Whenever there are dedicated ramps being retrofitted to an existing structure in an existing median, there are more complexities than with standard new highway design, often as a result of required clearances and interactions of the additional structure with the existing facility. dedicated access from overcrossings there would be no separate vehicle inspection stations either on the roadway or the ramp and it is assumed that the AHS vehicles are pre-approved elsewhere.

Median Width

A significant factor in construction costs of retrofit options is the median width. In general, where the median is sufficiently wide, lanes (buffer/transition lanes) can be added without additional right-of-way. If the existing median is narrow, then widening must occur on the outside of the highway. This outside widening may impact the overcrossings. If the overcrossings were planned by the local jurisdiction to accommodate widening of the highway then the overcrossings are probably long enough and do not have to be reconstructed. In this case the construction cost of widening to the inside or to the outside is approximately the same. If future widening was not planned then it is likely that the overcrossings will have to be reconstructed and that additional right-of-way will be required. The cost estimates developed herein include consideration that the existing median is too narrow so widening must occur on the outside of the highway and that reconstruction of the overcrossings will be required. It is also assumed that widening on the outside will require additional right-of-way. In situations where a structure, such as a pier column, will be located within a narrow median, the median would need to be widened to provide a minimum of two feet clearance from the face of the structure to the edge of the traveled way.

Verification of Mechanical and Electronic Adequacy of AHS Vehicles

The issue of verification of mechanical and electronic adequacy of AHS vehicles is not included in this report. However it must be recognized that whatever facilities are eventually used, there will be added infrastructure costs. These costs will be associated with vehicle reject lanes for non-compliant vehicles, on ramps for AHS vehicles and queuing areas for vehicles waiting to be inspected. Also not included in this report is the concept of holding bays. (That is a storage area for the AHS vehicle if/when the driver does not resume control of the vehicle at the end of the trip, i.e. the driver falls asleep).

Maintenance and Life Cycle Costs

The magnetic nail guidance system is a passive system within the highway. The only maintenance costs for the AHS would be occasional replacement of some magnetic nails if they become damaged and/or lose their magnetism. All other maintenance costs would be the same as for a conventional highway. Routine maintenance for highways includes an overlay of existing pavement. If the overlay is 4 inches or more the magnetic nails would likely need to be reset at a higher elevation in the pavement to remain effective.

Life cycle costs are negligible beyond the initial construction costs. The magnetic nail guidance system considered here is expected not to alter overall life cycle roadway costs. However, because life cycle costs are strongly determined by design, climate, roadway vehicle mix, and other factors, no general comment can be made at this time regarding the impact of additional electronic equipment installed on or near the roadway on the overall system life cycle costs. One maintenance/life cycle cost would be occasional replacement of some of the magnets if they become demagnetized. Another cost would be if the pavement is overlaid then the magnetic nails may require resetting at a higher elevation in the pavement to remain effective. Cost of resetting the magnetic nails at the same time pavement overlay is done is assumed to be negligible. Other Life cycle costs of the AHS facility are, except for the magnetic nails, the same as for a conventional highway.

General Design Considerations

One AHS retrofit option described below considers a dedicated separate elevated AHS facility (Option 5). If this AHS dedicated facility was to be used by automobiles only, the facility must still be designed to accommodate heavy vehicles such as busses and heavy emergency vehicles such as firetrucks.

Seismic consideration should not be a deterrent to using an elevated dedicated AHS structure based on recent advances in seismic bridge design.

Costs associated with construction in seismic zones are estimated to add no more than 2% to the overall cost of the project, but the reader is cautioned that seismic regulations vary by jurisdiction, cannot be considered optional, and cannot necessarily be extrapolated from one site to another.

4. Roadway Retrofit Options

In order to transition to a fully mature AHS facility, modifications to the existing roadway are necessary. For the purposes of this discussion the existing highway form upon which all retrofit options will be based is an existing eight lane (4 lanes in each direction) divided highway. Because highway costs are very site dependent and cannot be generically determined, we based our cost estimates on a ten mile segment of an existing highway, i.e. Route 101 in Los Angeles County (the Hollywood freeway). The choice of this length and this particular segment provides a representative combination of roadway and entry/exit ramp costs in a semi-urban setting that can be extended to longer or shorter segments. It traverses an urban area with some restrictions on right-of-way expansion, and is completely access controlled. A diagram of this section, taken from an existing map, is shown in Figure 1, for general informational purposes only. Table 1 (at the conclusion of this report) summarizes the key features of this roadway segment. Costs given later in this report are based on existing Caltrans log records of this segment. Any discrepancies should be resolved in favor of the estimation.

After examining the reference roadway, we determined that a single "one-modification-fits-all" scheme would not be possible. For maximum flexibility in the AHS implementation, we identified five fundamentally different options by which AHS can be implemented. These are different options for implementation of AHS and do not necessarily represent successive stages of AHS.

1) The existing four lanes remain in each direction and each lane is equipped with an automatic guidance system (magnetic nails embedded in the roadway).

2) A buffer lane is added to the existing four lanes resulting in three regular lanes, a buffer lane, and an automated lane (shared on/off ramp).

3) The same as in 2) above except that the AHS lane has dedicated on/off ramps on a bridge, thus the buffer zone cannot be used for traffic.

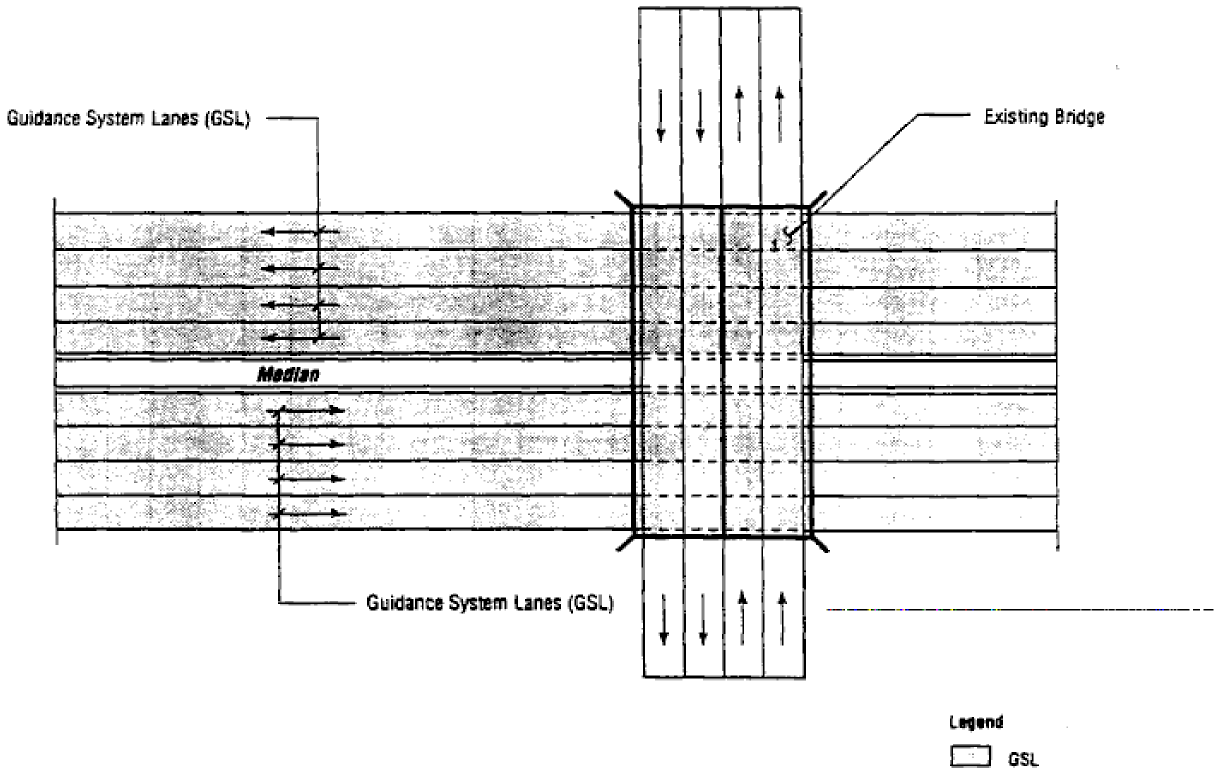
4) One of the four lanes is automated and delineated only with paint stripes or rumble strips.

5) A dedicated elevated structure is added for the automated lane with dedicated on/off ramps.

Although different implementation options would be used at various locations by considering urban versus rural environment and whether parallel routes exist and also the levels of traffic and congestion and socio-economics of the area (vehicle owners that might have AHS equipped vehicles, the five different cost estimates given below are based on the continuous implementation of each option over the entire 10 mile segment.

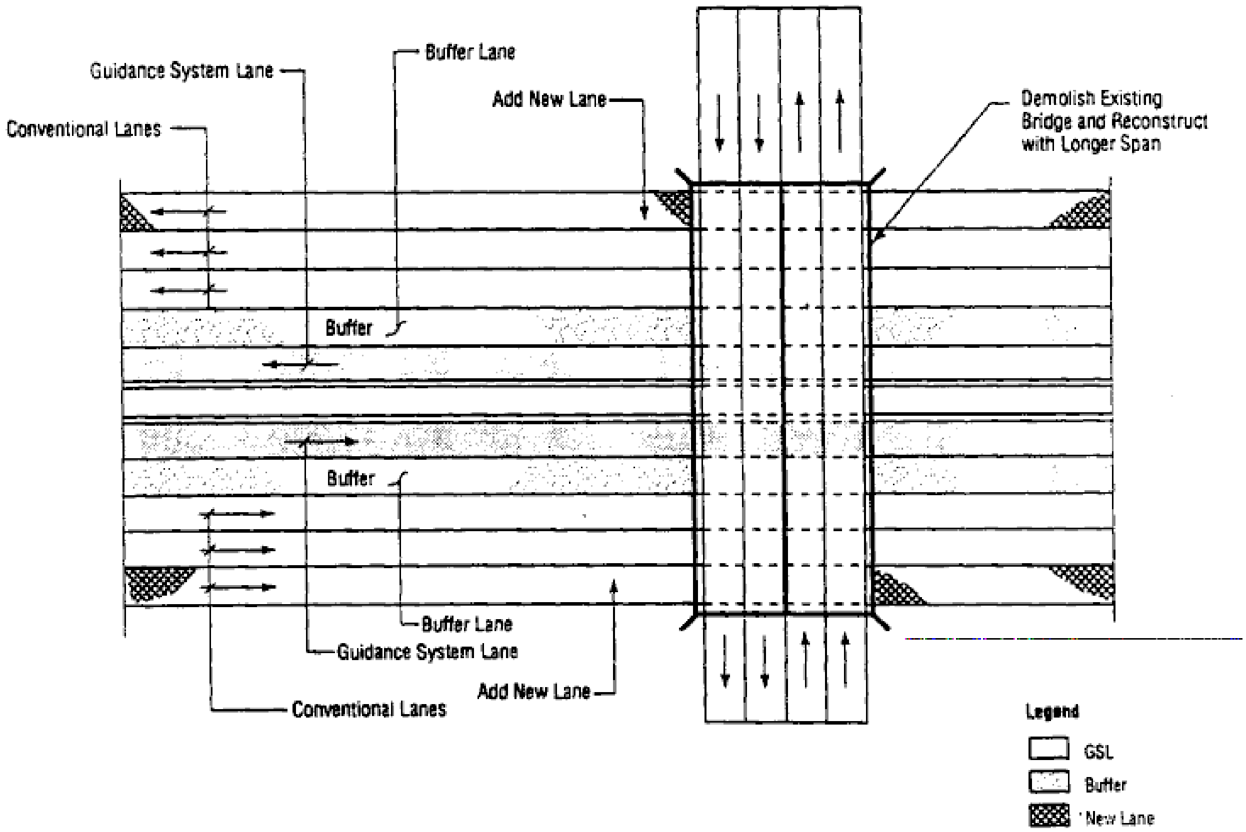
Details of Retrofit Options

Option 1. This option, although one of the least expensive, represents the most sophisticated form. All four lanes are automated with AHS guidance system and will appear and function as normal lanes to non-automated vehicles. The entire highway could be dedicated exclusively to AHS travel. Since all lanes would be automated, there will be no need to separate lanes beyond existing methods. However if mixed traffic was allowed to use the facility the overall capacity would be reduced. Construction of this option requires all lanes to be retrofitted with a guidance system. No other changes are required to the roadway. A vehicle inspection station would be required, but is not costed here.



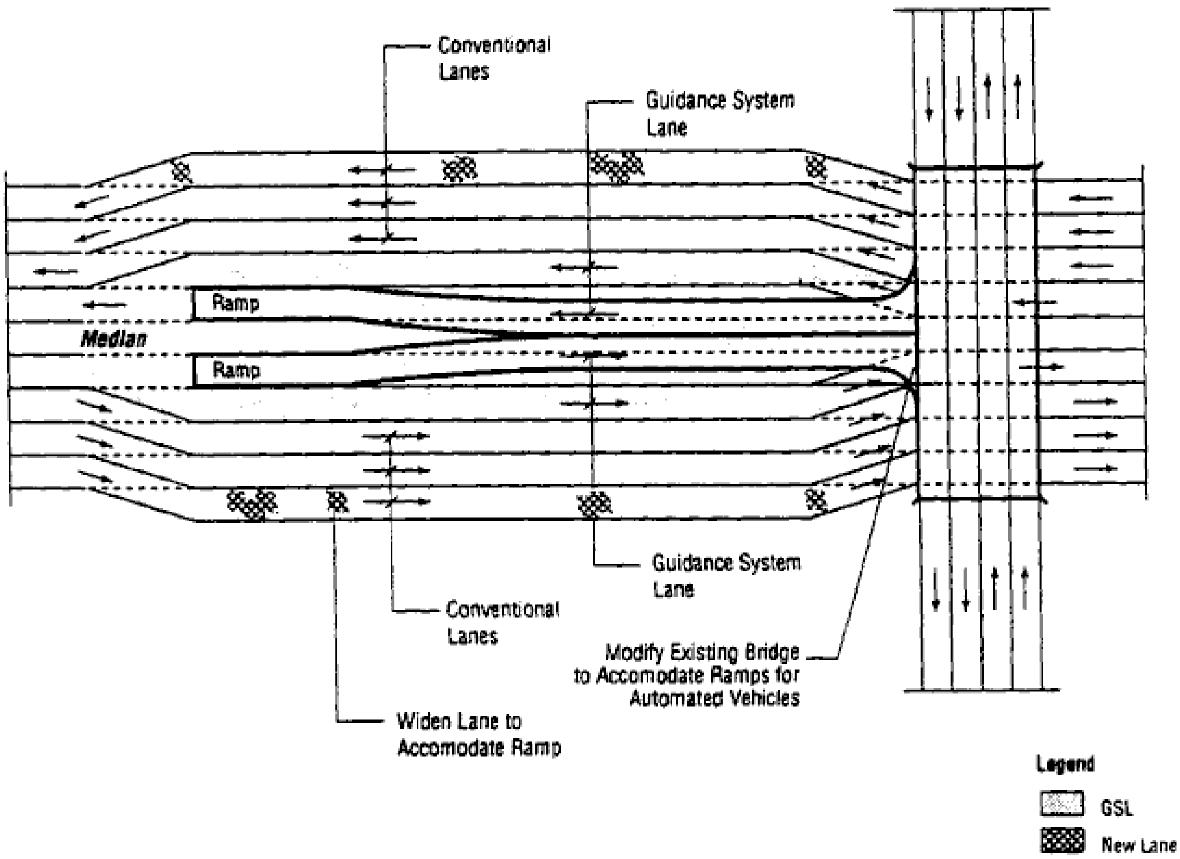
Option 1 All Lanes Automated

Option 2. At first glance, this option, which adds one lane to create a total of five lanes per direction (one lane automated, one buffer lane, and three lanes to remain conventional traffic), seems relatively simple. However, in adding a buffer lane there is a domino effect for the required construction. This buffer lane requires construction of a new lane on the outside to compensate for the loss of pavement due to the addition of the lane. This new lane, making the freeway wider, will in turn require demolition and reconstruction of all overcrossings to provide a longer clear span over the freeway, widening of the undercrossings, extension of culverts, relocation of signs and lighting etc. This option would also require use of retaining walls due to restricted space and embankments. It is likely that additional right-of-way will be required. Use of this option is severely restricted in some cases, especially well-developed areas, due to the high cost of additional right-of-way. However it is expected to constitute a particularly useful option in growing areas where traffic volume can be expected to steadily increase with or without the addition of an AHS option. The buffer lane is largely used for the necessary merging between AHS and conventional traffic but could be the site of some check-in-motion testers (assuming they are flush with the roadway) of AHS requisite equipment, should that equipment become available in the future.



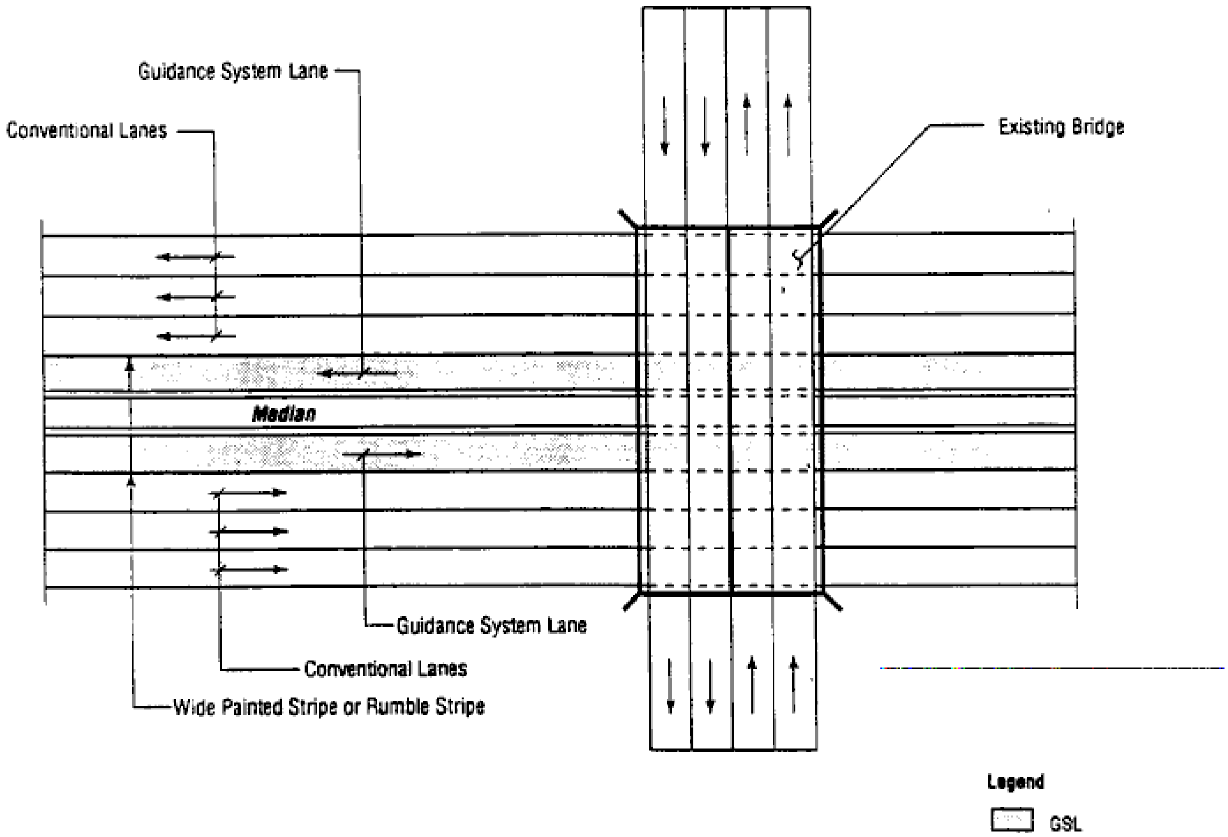
Option 2 One Lane Automated – Three Lanes Conventional
Buffer Lane Added Between Automated and Conventional Lanes

Option 3. One lane automated, one buffer lane, and three conventional lanes, as described above, but dedicated on/off ramps for automated lane entrances and exits into buffer lane from overhead structures such as bridges. This option is similar to Option 2 above except that the AHS lane has dedicated on/off ramps connecting to the center of the overcrossing bridges. This option has many of the advantages and disadvantages of the preceding option. The primary advantage is elimination of weaving on the roadway to access the automated lane. The AHS lanes ramp down and up and this ramp area is located where the buffer lane would be in option 2. Because of the ramp/retaining walls the buffer zone cannot be used for traffic. The buffer lane remains essentially unproductive except for its capacity to feed the automated lane. In this option a continuous concrete barrier is needed between the automated section and the conventional section.



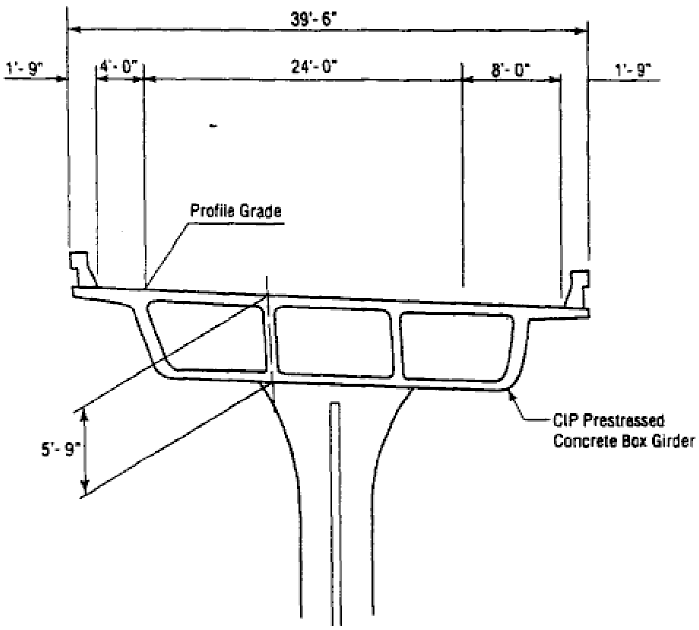
Option 3 (Similar to Option 2) Without Buffer On/Off Ramps Added with Bridge Structure

Option 4. In this option only the inside lane of the existing four lanes is retrofitted with the magnetic nails. That lane is delineated from conventional lanes with either wide painted stripes or rumble strips (e.g. dots on lane stripes). No additional right of way is anticipated for this option. If required, AHS lanes would be made narrower to compensate for small additional right of way requirements. The construction items in this option consist of magnetic nails in one lane and installation of traffic striping and or application of rumble strips. These rumble strips would not be the asphalt bumps, as this would be a traffic hazard, but could be either cut grooves, raised pavement dots or other types of devices that perform the same function. This option is the least expensive option. This option follows a precedent in Los Angeles, where striping and signs provides the only demarcation of certain HOV lanes. Exclusion is by traffic enforcement where substantial fines are levied for violation of the specially designated lane.

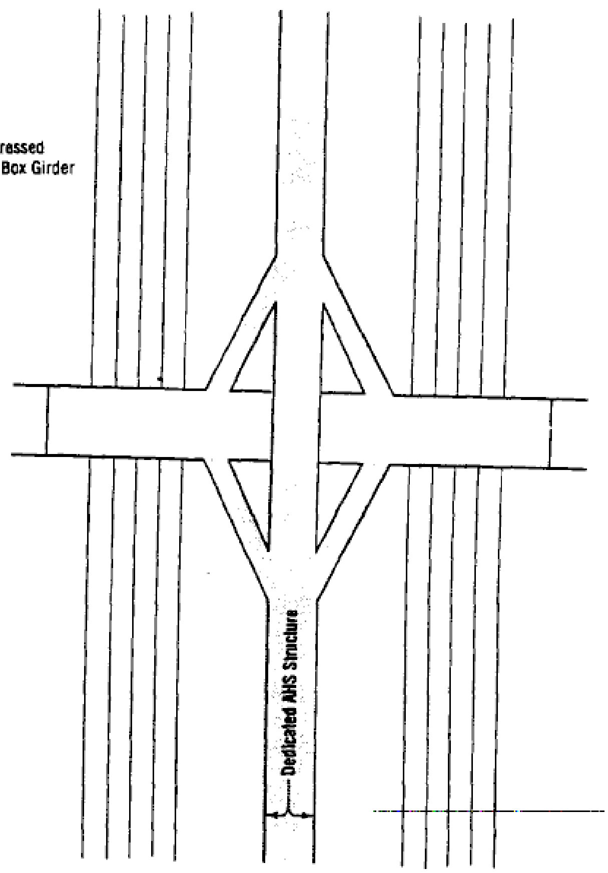


Option 4 One Lane Automated in Each Direction
Three Lanes to Remain Conventional
Separation by Wide Striping or Rumble Strips

Option 5. In this option the four lanes of the existing highway remain unchanged. An elevated dedicated structure, is added to the base highway for the automated lane with its own on/off ramps. This structure is anticipated to follow the existing highway right-of-way for the most part, and if part of the highway would probably be built in the median of the highway. For the cost estimate the structure is assumed to be located in the median. The footings of the columns in the median could interfere with the drainage system and could possibly require special drainage considerations.



Option 5 Dedicated AHS Structure – Elevation



Option 5 AHS Access at Overcrossing – Plan

New roadway construction along alternate right-of-ways (e.g. utility corridors) can, in general be extrapolated from Option 5 above.

The cost of the elevated option might intuitively seem to be the most costly option. However it should be noted that the cost of Option 5 constructed in the center of the road corridor,the dedicated AHS elevated option, is less than either Option 2 or Option 3. The structure cost for Option 5 is almost double the structure cost of Option 2 and Option 3. However this is more than offset by the additional right-of-way, utililty relocation, retaining walls, and new paving required for Options 2 and 3, in addition to reconstruction of the existing overcrossings.

5. Assumptions Underlying Cost Estimates

The conceptual nature of this study necessitates assumptions for both AHS development and for estimating costs of the various retrofit options. The AHS development assumptions are as follows:

- There are enough AHS equipped vehicles in use that the construction of an AHS highway is feasible.
- The impact of construction of the project on the area is not severe and can be mitigated. It is presumed that an environmental document could be approved.
- It is assumed that problems associated with magnetic nail interference from steel reinforcement (rebar) in concrete and the steel mass in steel bridges will be overcome.

Assumptions used as basis for the cost estimates are as follows:

a) Pricing is based on first quarter 1994 levels. No escalation is included.

b) Costs are consistent with a competitively-bid, Caltrans-administered highway project.

c) Construction cost estimates include a 10% mobilization and a 20% contingency.

d) The right-of-way cost estimate included land acquisition at $25.00 per square foot. No additional contingency is applied to the right-of-way costs.

e) The number of access points for AHS dedicated on/off ramps is approximately the same as for conventional on/off ramps.

f) Installation costs are included as well as land acquisition.

The cost estimates include only the capital cost associated with land acquisition, utility relocation and construction. Except for the embedded magnetic nails, no costs are included for the AHS control system or the vehicles. These costs are assumed to be included in the vehicle electronics cost report.

No specific costs are included for program management services, design, construction management services, fees, or related activities. These items are essential parts of any real-world highway project, but their magnitude varies substantially due to (i) the type of contract format; (ii) the absolute size of the job; (iii) the complexity of the work tasks; and (iv) the level of market risk assumed by the contractor at the time when bid is submitted. Approximate industry averages of benchmark values based on overall industry experience, involving both conventional and first-of-a-kind large civil systems projects, are as follows:

- for construction management services, 4% of the sum of all non-labor costs and any applicable sales tax
- for design management, engineering, and systems integration services, 10% of the sum of all non-labor costs, any applicable sales tax, and construction management fees
- for procurement management and related project controls services, 4% of the sum of all non-labor costs, any applicable sales tax, and construction management fees

Contingencies are often assumed to be on the order of 20% of total costs, as noted above. A reasonable benchmark for fees would be 2.5%. Sales tax rates vary, both county by county and state by state. Labor-related and other escalation values are highly volatile as a function of the national construction market for large jobs; during the last few years they have been relatively flat.

Extensive past experience suggests that maintenance costs, especially in comparison with the construction costs, can be expected to be nominal. When Caltrans, for example, does a cost/benefit analysis, maintenance costs are not usually a consideration as the maintenance costs would be approximately equal for most study alternatives. For the AHS retrofit options, other than routine maintenance, the only anticipated maintenance would be occasional replacement of some of the magnets if they either become demagnetized, or if in the course of resurfacing the roadway, the cover exceeds 4 inches. If the overlay exceeds four inches, the magnetic nails would have to be reset to a higher elevation. We have no data to indicate how often replacements due to demagnetization would be required, nor do we have good reason to believe it will be frequent. Resurfacing of the roadway is a normal highway maintenance cost that is nominal compared to costs of new construction and would typically occur on average at 15 year intervals.

Since automating a roadway is not expected to impact the conventional maintenance requirements for a roadway, no maintenance or life cycle costs are included in these estimates. In fact, automation may have a positive effect. The design of highway road beds and highway structures are ordinarily based on truck traffic volumes and speeds. Trucks, by virtue of their weight, cause significantly greater deterioration to the roadway than do lighter vehicles. If the automated lanes are not used by trucks, we can assume that no additional roadway maintenance will be required and that the roadway life may be prolonged over conventional, mixed use, roadways.

Option specific assumptions:

Options 3 and 5 provide dedicated access for the AHS lanes. Access is assumed to be from the overcrossings.

The dedicated elevated structure, (Option 5) is assumed to be 40 feet wide.

6. Constraints

In many urban areas, widening the roadway such as in options 2 and 3 would not be feasible through most of the highway corridor due to primarily to right-of-way and environmental constraints.

1). Right-of-way constraints:

- In some areas right-of-way is simply not available

- In other areas the acquisition would undermine existing structures some of which will be very costly to replace.

- Ramps and other roadway infrastructure will require additional right-of-way.

2) Environmental Constraints

- Environmental mitigation costs will add to the cost of construction

- Additional lanes imply, and possibly induce additional traffic

For the purposes of this study we used a 10 mile segment of the Hollywood Freeway to give a common point of reference for our cost estimates, allowing all 5 options to be considered. Although right-of-way is still expensive, this section was used because it is anticipated that the right-of-way and environmental problems here would not be insurmountable as they might be on other highways.

However, right-of-way costs and environmental mitigation costs very widely by location. *For example Route 101 in a rural setting, (or any other highway in a rural setting) would have reduced right-of-way costs, reduced utility relocation costs, and require less retaining walls. Environmental mitigation costs such as sound walls would also be reduced. A rural setting would give more geometric options which would help optimize design and construction costs. Also a rural setting typically has less traffic congestion and would require less construction staging, traffic control and detours.*

Delays in the design and construction schedule due to the environmental problems and mitigation will cause escalation in the overall cost of the project.

7. Cost Estimates

The following pages give cost estimates for each retrofit option. The first set of pages contain a summary of the cost estimates. Details of each cost estimate are included as an appendix to this report.

Construction cost estimates are based on recent historical data for competitively-bid, state-administered California highway projects. Most of the data is derived from Santa Clara County's "Measure A" Highway Program. This is a ten-year program, funded by a county sales tax. The program includes about $600 million in construction on urban freeways in Santa Clara County. Much of the work is very similar in nature the the freeway widening options for the AHS study presented here. Specifically, the basis for estimating AHS construction costs is the State of California Caltrans' Construction Cost Data Book. This book gives the actual costs of contract bid items for actual Caltrans highways construction projects. It shows the total number of items installed per project and the average cost per item per project and the averages for the entire state of California. The costs used for estimates given here are taken directly from this book where applicable, or extrapolated from values in this book where necessary.

Essentially all work performed on state highways in California must be done in accordance with Caltrans specifications and procedures, and therefore a high degree of uniformity can be expected when developing the basic parameters for construction cost estimating.

These cost estimates do not include any special provisions for direct freeway-to-freeway AHS connections. It is assumed, for the purposes of these estimates, that AHS vehicles will resort to using existing ramps and lanes when merging onto an adjoining freeway.

Most of the costs are material and construction costs. However, there are other costs for tasks needed to safely implement the AHS system that are necessarily a function of the method of implementation (e.g. lane closures). For these costs we give a best guess estimate based on past experience.

The construction cost estimates are segregated into 16 separate cost categories. Our estimator developed this format several years ago and has used it extensively for estimates throughout the state of California. Summarizing the estimates in the format given has been shown to have many advantages during the conceptual stage of project development through the final design stage. The line items in each detailed estimate evolve from the gross parameters (e.g. $/sf for bridges) to the final Caltrans bid item list (e.g. 30-40 items for a bridge). As long as all the costs are rolled up into the basic categories, it is straightforward to compare and reconcile costs through the life of a project and to extrapolate the information in other estimates.

Figure 1
Diagram of Representative Highway Section
used as basis for Cost Estimates in this Report

Table 1: Characteristics of Roadway Segment Used for Costing Purposes

The highway segment selected for this analysis has the following **characteristics:**

34	Overcrossings (local street over highway)
28	Undercrossings (highway over local street)
I	Pedestrian Overcrossing *(pedestrians* over highway)
8	Pedestrian Undercrossing (pedestrians under highway)
7	Separation Structures (crossing state highways)
4	Pump plants
4	Bridge and/or Overheads (highway over water and/or railroad)
1	Underpass (railroad over highway)
1	Box culvert (storm drainage)
4	Connectors (highway-to-highway ramps)

92 total structures listed in Caltrans bridge log.

Northbound: 18 on-ramps and 18 off-ramps
Southbound: 19 on-ramps and 21 off-ramps

The structures are relatively old, as indicated by the following tabulation of date of original construction:

1930's	1 structure
1940's	38 structures
1950's	44 structures
1960's	4 structures
1970's	3 structures
1980's	2 structures
1990's	0 structure

92 total structures listed in Caltrans bridge log.

The age of the structures would imply that there are many substandard features that may be very costly to bring up to current specifications. These features may include horizontal and vertical clearances, lane and shoulder widths, radii of horizontal and vertical curves, profile grades, weaving and merging distances, sight distances, spacing of interchanges or ramps, compliance with noise standards, seismic requirements, capacity of storm drainage systems, etc.

AUTOMATED HIGHWAY SYSTEM - BASIS OF COST ESTIMATES

1) Construction cost estimates are based on the following:

   a) Pricing is based on *first* quarter 1994 levels. No escalation is included.

   b) Costs are consistent with a competitively-bid, Caltrans-administered highway project.

   c) Construction cost estimates include a 10% mobilization and a 20% contingency.

   d) The right-of-way cost estimate includes land acquisition at $25.00 per square foot. No additional contingency is applied to the right-of-way costs.

2) The cost estimates include only the capital cost associated with land acquisition, utility relocation, and construction. Except for the embedded magnets, no costs are included for the AHS control system or the vehicles.

3) No cost is included for program management, design, construction support, or construction management.

4) Options 3 and 5 provide dedicated access for the AHS lanes. Access is assumed at the following locations:

A.H.S. Access locations for Option 3 and S

Location	Description	Post Mile	Distance
Sixth Street	Overcrossing	0.20	---
Mission Road	Undercrossing	1.28	1.08
Grand Avenue	Overcrossing	1.32	1.19
Alvarado Blvd	Undercrossing	2.86	1.54
Vermont Avenue	Overcrossing	4.40	1.54
Santa Monica Blvd	Overcrossing	5.54	1.14
Hollywood Blvd	Overcrossing	6.52	0.98
Route 170	Overcrossing	7.84	1.32
Barham Blvd	Overcrossing	9.22	1.38

Attachments 1 and 2 show the interchange configurations for Option 3.
Attachments 3 and 4 show the interchange configurations for Option 5.

5) The viaduct for the AHS lanes in Option 5 is assumed to be 40 feet wide. Attachment 5 shows a similar viaduct.

IVHS\SUMMARY2

AUTOMATED HIGHWAY SYSTEM – SUMMARY OF COST ESTIMATES | 07–LA–101–0.0/10.0

Item	Description	Option 1	Option 2	Option 3	Option 4	Option 5
01	Mass Earthwork	0	6,033,333	8,283,333	0	5,000,000
02	Retaining Walls	0	19,008,000	21,600,000	0	5,184,000
03	Bridges	0	65,877,200	83,886,800	0	149,320,000
04	Pavement	0	13,027,680	14,755,680	0	215,200
05	Soundwalls	0	6,652,800	6,652,800	0	0
06	Landscaping and Erosion Control	0	1,000,000	1,000,000	0	0
07	Pedestrian and Bicycle Facilities	0	250,000	400,000	0	100,000
08	Signalization and Lighting	0	3,000,000	5,250,000	0	2,250,000
09	Drainage and Creek Channel Improvements	0	5,000,000	7,700,000	0	2,250,000
10	Barrier and Guard Railing	0	2,084,000	4,421,000	0	225,000
11	Signage	150,000	3,000,000	3,450,000	150,000	450,000
12	Striping	0	2,000,000	2,180,000	528,000	380,000
13	Construction Support and Detours	2,220,000	17,084,000	21,584,000	1,120,000	21,584,000
14	Existing Facilities – Remove, Salvage, Relocate, etc	0	10,000,000	10,450,000	0	5,000,000
15	Utility Relocation incl in Construction Contract	0	15,000,000	15,900,000	0	5,000
16	Other Itemized Costs	4,490,000	6,850,000	7,225,000	1,850,000	4,225,000
Subtotal		**6,860,000**	**175,867,013**	**214,738,613**	**3,648,000**	**196,188,200**
17	Mobilization	686,000	17,586,701	21,473,861	364,800	19,618,820
Total Bid Level Cost		**7,546,000**	**193,453,714**	**236,212,474**	**4,012,800**	**215,807,020**
18	State Furnished Materials and Expenses	300,000	4,000,000	4,500,000	50,000	4,000,000
Subtotal		**7,846,000**	**197,453,714**	**240,712,474**	**4,062,800**	**219,807,020**
19	Contingency	1,569,200	39,490,743	48,142,495	812,560	43,961,404
Total Construction Cost		**9,415,200**	**236,944,457**	**288,854,969**	**4,875,360**	**263,768,424**
20	Land Acquisition	0	51,490,000	67,690,000	0	16,200,000
21	Utility Relocation	0	25,000,000	27,250,000	0	2,250,000
Total Right–of–way Cost		**0**	**76,490,000**	**94,940,000**	**0**	**18,450,000**
Total Construction Cost plus Right–of–way Cost		**9,415,200**	**313,434,457**	**383,794,969**	**4,875,360**	**282,218,424**

IVHS\SUM1A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	Mass Earthwork					0
02	Retaining Walls					0
03	Bridges					0
04	Pavement					0
05	Soundwalls					0
06	Landscaping and Erosion Control					0
07	Pedestrian and Bicycle Facilities					0
08	Signalization and Lighting					0
09	Drainage and Creek Channel Improvements					0
10	Barrier and Guard Railing					0
11	Signage					150,000
12	Striping					0
13	Construction Support and Detours					2,220,000
14	Existing Facilities – Remove, Salvage, Relocate, etc					0
15	Utility Relocation incl in Construction Contract					0
16	Other Itemized Costs					4,490,000
Subtotal						6,860,000
17	Mobilization				10.0%	686,000
Total Bid Level Cost						7,546,000
18	State Furnished Materials and Expenses					300,000
Subtotal						7,846,000
19	Contingency				20.0%	1,569,200
Total Construction Cost						9,415,200

20	Land Acquisition	0
21	Utility Relocation	0
Total Right–of–way Cost		0

Total Construction Cost plus Right–of–way Cost	9,415,200

IVHS\SUM1A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	**Mass Earthwork**					**0**
(a)	No mass earthwork required.	---	---	---	---	0
02	**Retaining Walls**					**0**
(a)	No retaining walls required.	---	---	---	---	0
03	**Bridges**					**0**
(a)	No bridges required.	---	---	---	---	0

IVHS\SUM1A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
04	**Pavement**					**0**
(a)	No pavement required.	---	---	---	---	0
05	**Soundwalls**					**0**
(a)	No soundwalls required.	---	---	---	---	0

IVHS\SUM1A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
06	**Landscaping and Erosion Control**					**0**
(a)	No landscaping and erosion control required.	---	---	---	---	0
07	**Pedestrian and Bicycle Facilities**					**0**
(a)	No pedestrian and bicycle facilities required.	---	---	---	---	0
08	**Signalization and Lighting**					**0**
(a)	No signalization and lighting required.	---	---	---	---	0

IVHS\SUM1A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
09	**Drainage and Creek Channel Improvements**					**0**
(a)	No drainage and creek channel improvements required.	---	---	---	---	0
10	**Barrier and Guard Railing**					**0**
(a)	No barrier and guard railing required.	---	---	---	---	0
11	**Signage**					**150,000**
(a)	Allowance for signage.	MILE		10	15,000	150,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
12	**Striping**					**0**
(a)	No striping required.	---	---	---	---	0
13	**Construction Support and Detours**					**2,220,000**
(a)	Detours and other temporary construction. Not required.	---	---	---	---	0
(b)	Temporary signage, striping, lighting, etc. Not required.	---	---	---	---	0
(c)	Traffic control during construction.	LS				2,000,000
(d)	Temporary railing (Type K) – Not required.	---	---	---	---	0
(e)	Construction staking. Not required.	---	---	---	---	0
(f)	Develop water supply. Not required.	---	---	---	---	0
(g)	Contractor is required to provide a monthly critical path schedule update. This is a contract bid item.	LS				20,000
(h)	Other misc construction support costs.	LS				200,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
14	**Existing Facilities – Remove, Salvage, Relocate, etc**					0
(a)	No work required.	---	---	---	---	0
15	**Utility Relocation incl in Construction Contract**					0
(a)	No utility relocation required.	---	---	---	---	0
16	**Other Itemized Costs**					4,490,000
(a)	Allowance for other costs. Not required.	---	---	---	---	0
(b)	Furnish and install A.H.S. magnets. Assume purchase cost of magnets is $1.00 each. Assume magnets are 4.0 inches long, 1.0 inch diameter, 2.0 inches deep, and spaced at an interval of 3.0 feet.	EA	(8*10*5280)/3	140,800	25.00	3,520,000
(c)	Furnish and install 20 ft poles for video coverage. Assume one line of poles in the median, spaced at 165 ft (32 per mile). Include hookup to power and phone lines. Exclude video equipment.	EA	10*5280/165	320	2,500	800,000
(d)	Install Local Control Center (LCC). LCC's are required at 5 mile intervals.	EA	10/5	2	10,000	20,000
(e)	Install Master Control Center (MCC). MCC's are required at 50 mile intervals. Assume MCC will be located in an existing state–owned facility, so no land acquisition is required. Assume facility is a habitable building about 1,000 square feet, incorporating a relatively high level of security measures.	EA		1	100,000	100,000
(f)	Install equipment rack at on–ramps. Assume installation requirements will be similar to a signal controller.	EA	2*10	20	2,500	50,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 1	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
18	**State Furnished Materials and Expenses**					**300,000**
(a)	Resident engineer's office.	LS				250,000
(b)	Sign panels. Not required.	LS				0
(c)	Traffic signal controllers. Not required.	---	---	---	---	0
(d)	Other misc items.	LS				50,000
20	**Land Acquisition**					**0**
(a)	No land acquisition required.	---	---	---	---	0
21	**Utility Relocation**					**0**
(a)	No utility relocation required.	---	---	---	---	0

IVHS\SUM2A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	Mass Earthwork					6,033,333
02	Retaining Walls					19,008,000
03	Bridges					65,877,200
04	Pavement					13,027,680
05	Soundwalls					6,652,800
06	Landscaping and Erosion Control					1,000,000
07	Pedestrian and Bicycle Facilities					250,000
08	Signalization and Lighting					3,000,000
09	Drainage and Creek Channel Improvements					5,000,000
10	Barrier and Guard Railing					2,084,000
11	Signage					3,000,000
12	Striping					2,000,000
13	Construction Support and Detours					17,084,000
14	Existing Facilities – Remove, Salvage, Relocate, etc					10,000,000
15	Utility Relocation incl in Construction Contract					15,000,000
16	Other Itemized Costs					6,850,000
Subtotal						175,867,013
17	Mobilization				10.0%	17,586,701
Total Bid Level Cost						193,453,715
18	State Furnished Materials and Expenses					4,000,000
Subtotal						197,453,715
19	Contingency				20.0%	39,490,743
Total Construction Cost						236,944,458

20	Land Acquisition	51,490,000
21	Utility Relocation	25,000,000
Total Right–of–way Cost		76,490,000

Total Construction Cost plus Right–of–way Cost	313,434,458

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	**Mass Earthwork**					**6,033,333**
(a)	Assume average cross section of 30 ft width by 5 ft depth on both sides for 50% of project length.	CY	(0.5*10*5280*2*30*5)/27	293,333	10.00	2,933,333
(b)	Additional earthwork at reconfigured ramps. Assume 40 ramps with 1,500 CY per ramp.	CY	40*1500	60,000	10.00	600,000
(c)	Allowance for removal of contaminated soil.	CY		25,000	100.00	2,500,000
02	**Retaining Walls**					**19,008,000**
(a)	Assume retaining walls are required for 25% of project length, with average height of 12 ft.	SF	0.25*10*5280*2*12	316,800	60.00	19,008,000
03	**Bridges**					**65,877,200**
(a)	See the bridge estimate attached.	LS				65,877,200
	This item includes the cost of all vehicle, pedestrian, and railroad structures. The cost also includes any required demolition of existing structures.					

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
04	**Pavement**					**13,027,680**
(a)	Construct new travelled lanes.	SF	10*5280*2*12	1,267,200	4.00	5,068,800
(b)	Construct new outside shoulders.	SF	10*5280*2*10	1,056,000	2.50	2,640,000
(c)	Allowance for reconstruction of major local streets. Assume 10 each by 600 ft by 84 ft.	SF	10*600*84	504,000	3.00	1,512,000
(d)	Allowance for reconstruction of minor local streets. Assume 20 each by 500 ft by 50 ft.	SF	20*500*50	500,000	3.00	1,500,000
(e)	Allowance for reconstruction of ramps. Assume 40 each by 500 ft by 30 ft.	SF	40*500*30	600,000	3.00	1,800,000
(f)	Allowance for additional paving required due to revised profiles and alignments. Assume 10% of total cost of item 04(a).	LS	0.1*H71	506,880	1.00	506,880
05	**Soundwalls**					**6,652,800**
(a)	Assume soundwalls are required for 30% of project length, with average height of 14 ft.	SF	0.3*10*5280*2*14	443,520	15.00	6,652,800

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
06	**Landscaping and Erosion Control**					**1,000,000**
(a)	Assume the corridor is too narrow to accommodate mainline landscaping. Assume 2.0 acres of landscaping are required at each of 10 interchanges.	ACRE	2*10	20	50,000	1,000,000
07	**Pedestrian and Bicycle Facilities**					**250,000**
(a)	Pedestrian overcrossings and undercrossings are included with item 03–Bridges. Provide an additional allowance for facilities necessary to maintain pedestrian and bicycle access.	LS				250,000
08	**Signalization and Lighting**					**3,000,000**
(a)	Assume major signalization and lighting modifications are required at 20 locations. Assume that most of the existing equipment can be salvaged and re–used.	EA		20	150,000	3,000,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2						07–LA–101–0.0/10.0
Item	**Description**	**Unit**	**Calculation**	**Quantity**	**Unit Cost**	**Total Cost**
09	**Drainage and Creek Channel Improvements**					**5,000,000**
(a)	Assume no major work is required at the Los Angeles River or at other creek crossings. Assume no major modifications are required to longitudinal drainage systems or interceptors. Provide an allowance for freeway drainage.	MILE		10	500,000	5,000,000
10	**Barrier and Guard Railing**					**2,084,000**
(a)	There is an existing concrete or metal beam barrier in the freeway median for essentially the total length of the corridor. Assume 25% of this barrier will need to be replaced due to realignments, profile changes, etc.	LF	0.25*10*5280	13,200	40.00	528,000
(b)	Allowance for additional barrier or guard railing required on the outside shoulders. Assume 25% of the total freeway length.	LF	0.25*2*10*5280	26,400	40.00	1,056,000
(c)	Allowance for additional barrier or guard railing required at ramps and local streets.	LS				500,000
11	**Signage**					**3,000,000**
(a)	Allowance.	MILE		10	300,000	3,000,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
12	**Striping**					**2,000,000**
(a)	Allowance.	MILE		10	200,000	2,000,000
13	**Construction Support and Detours**					**17,084,000**
(a)	Detours and other temporary construction.	LS				5,000,000
(b)	Temporary signage, striping, lighting, etc.	LS				2,000,000
(c)	Traffic control during construction.	LS				5,000,000
(d)	Temporary railing (Type K) – Assume full length of corridor on both sides. Add 25% for interchanges and local streets.	LF	10*5280*2*1.25	132,000	12.00	1,584,000
(e)	Construction staking.	LS				2,000,000
(f)	Develop water supply.	LS				500,000
(g)	Contractor is required to provide a monthly critical path schedule update. This is a contract bid item.	LS				500,000
(h)	Other misc construction support costs.	LS				500,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2						07–LA–101–0.0/10.0
Item	**Description**	**Unit**	**Calculation**	**Quantity**	**Unit Cost**	**Total Cost**
14	**Existing Facilities – Remove, Salvage, Relocate, etc**					**10,000,000**
(a)	Allowance for removal, salvage, relocation, etc of minor items such as sidewalks, guardrails, signs, drainage structures, etc.	LS				10,000,000
	This cost excludes the removal of existing bridge structures, which are included in item 03–Bridges.					
15	**Utility Relocation incl in Construction Contract**					**15,000,000**
(a)	Allowance for utility relocations to be performed by state's contractor. This will include primarily local sewer and water lines.	LS				15,000,000
16	**Other Itemized Costs**					**6,850,000**
(a)	Allowance for other costs, including: Minor concrete (curb, gutter, sidewalk, etc.); Fencing and gates; Survey monuments.	LS				5,000,000
(b)	Furnish and install A.H.S. magnets. Assume purchase cost of magnets is $1.00 each. Assume magnets are 4.0 inches long, 1.0 inch diameter, 2.0 inches deep, and spaced at an interval of 3.0 feet.	EA	(2*10*5280)/3	35,200	25.00	880,000
(c)	Furnish and install 20 ft poles for video coverage. Assume one line of poles in the median, spaced at 165 ft (32 per mile). Include hookup to power and phone lines. Exclude video equipment.	EA	10*5280/165	320	2,500	800,000
(d)	Install Local Control Center (LCC). LCC's are required at 5 mile intervals.	EA	10/5	2	10,000	20,000
(e)	Install Master Control Center (MCC). MCC's are required at 50 mile intervals. Assume MCC will be located in an existing state–owned facility, so no land acquisition is required. Assume facility is a habitable building about 1,000 square feet, incorporating a relatively high level of security measures.	EA		1	100,000	100,000
(f)	Install equipment rack at on–ramps. Assume installation requirements will be similar to a signal controller.	EA	2*10	20	2,500	50,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2						07–LA–101–0.0/10.0
Item	**Description**	**Unit**	**Calculation**	**Quantity**	**Unit Cost**	**Total Cost**
18	**State Furnished Materials and Expenses**					**4,000,000**
(a)	Resident engineer's office.	LS				1,500,000
(b)	Sign panels.	LS				1,000,000
(c)	Traffic signal controllers.	LS				1,000,000
(d)	Other misc items.	LS				500,000
20	**Land Acquisition**					**51,490,000**
(a)	Assume an average width of 30 ft must be acquired for the entire length of the corridor.	SF	10*5280*30	1,584,000	25.00	39,600,000
(b)	Assume an additional 1.0 acre will be required at each of 10 interchange areas.	SF	10*1*43560	435,600	25.00	10,890,000
(c)	Allowance for preservation or relocation of historical, archaeological, or cultural resources.	LS				1,000,000
21	**Utility Relocation**					**25,000,000**
(a)	Allowance for major utility relocations to be performed by the utility companies or their contractors (excl. railroads).	LS				20,000,000
(b)	Allowance for railroad relocations or modifications to be performed by the railroad companies or their contractors.	LS				5,000,000

IVHS\BRIDGE2

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
TOTAL COST – PAGES 1 thru 10														65,877,200	
									Summary of Unit Costs:						
									Construct new overcrossing.	SF	---	---	80.00		
									Construct new ped overcrossing.	SF	---	---	100.00		
									Construct new railroad underpass.	SF	---	---	200.00		
									Extend existing box culvert.	SF	---	---	150.00		
									Extend existing ped undercrossing.	SF	---	---	150.00		
									Remove existing overcrossing.	SF	---	---	20.00		
									Remove existing ped overcrossing.	SF	---	---	20.00		
									Remove existing railroad underpass.	SF	---	---	30.00		
									Widen existing undercrossing.	SF	---	---	100.00		

ASSUMPTIONS:

1) Assume that existing overcrossings and underpasses will not accommodate freeway widening, and must be demolished and replaced. Assume the new structure will be 30 feet longer than the original structure, but will remain the same width.

2) Assume that existing undercrossings, bridges, and overheads will be widened by a total of 30 feet.

IVHS\BRIDGE2

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2 | BRIDGE ESTIMATE | Route 101 – Hollywood Freeway in Los Angeles | 07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
1	53–1367–G	Route 5/10/101	Separation	0.01	753	48	1960	n/a	No modification req'd.						
2	53–0596	Seventh Street	O/C	0.02	209	68	1948	n/a	Remove existing O/C. Construct new O/C.	SF SF	209*68 239*68	14,212 16,252	20.00 80.00	284,240 1,300,160	
3	53–2644–L	Route 5/10/101	Separation	0.03	589	48	1960	n/a	No modification req'd.						
4	53–0595	Sixth Street	O/C	0.20	3,180	46	1932	n/a	Realign Rt.101 under O/C to accommodate widening.						
5	53–1357–S	Whittier Boulevard ramp	O/C	0.22	78	28	1960	n/a	No modification req'd.						
6	53–0583–W	Fourth Street Pump Plant	Pump Plant	0.60	n/a	n/a	1947	n/a	No modification req'd.						
7	53–0583	Fourth Street	O/C	0.62	167	56	1947	n/a	Remove existing O/C. Construct new O/C.	SF SF	167*56 197*56	9,352 11,032	20.00 80.00	187,040 882,560	
8	53–0582	First Street	U/C	0.91	188	78	1947	n/a	Widen existing U/C.	SF	188*30	5,640	100.00	564,000	
9	53–0555–L	Mission Road	U/C	1.28	171	24	1947	n/a	Widen existing U/C.	SF	171*15	2,565	100.00	256,500	
10	53–0555–R	Mission Road	U/C	1.28	208	24	1947	n/a	Widen existing U/C.	SF	208*15	3,120	100.00	312,000	
Subtotal Page 1														3,786,500	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
11	53–0881–F	Connector	O/C	1.32	798	28	1955	n/a	No modification req'd.						
12	53–0556–F	Route 10/101	Separation	1.32	48	n/a	1944	n/a	No modification req'd.						
13	53–1224	Los Angeles River	Bridge	10.83	137	124	1957	n/a	Widen existing bridge.	SF	137*30	4,110	100.00	411,000	
14	53–1225	Vineland Avenue	U/C	11.11	164	134	1957	1992	Widen existing U/C.	SF	164*30	4,920	100.00	492,000	
15	53–0405	Los Angeles River	Bridge O/H	0.08	1,651	128	1944	1955	Widen existing bridge O/H.	SF	1651*30	49,530	100.00	4,953,000	
16	53–2673a	Los Angeles River	O/H	0.37	2,571	54	1989	n/a	Widen existing O/H.	SF	2571*15	38,565	100.00	3,856,500	
17	53–2673b	Los Angeles River	O/H	0.46	2,571	54	1989	n/a	Widen existing O/H.	SF	2571*15	38,565	100.00	3,856,500	
18	53–0782–W	Alameda Street Pump Plant	Pump Plant	0.74	n/a	n/a	1954	n/a	No modification req'd.						
19	53–0782	Alameda Street	O/C	0.76	177	80	1954	1989	Remove existing O/C. Construct new O/C.	SF SF	177*80 207*80	14,160 16,560	20.00 80.00	283,200 1,324,800	
20	53–0799	Daniels (?)	U/P	0.80	185	n/a	1953	n/a	Remove existing U/P. Construct new U/P.	SF SF	185*20 215*20	3,700 4,300	30.00 200.00	111,000 860,000	
Subtotal Page 2														**16,148,000**	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
21	53–0629	Los Angeles Street	O/C	0.87	128	74	1950	n/a	Remove existing O/C. Construct new O/C.	SF SF	128*74 158*74	9,472 11,692	20.00 80.00	189,440 935,360	
22	53–0769	Los Angeles Street on–ramp	O/C	0.88	42	74	1950	n/a	No modification req'd.						
23	53–0628	Main Street	O/C	0.93	141	63	1950	n/a	Remove existing O/C. Construct new O/C.	SF SF	141*63 171*63	8,883 10,773	20.00 80.00	177,660 861,840	
24	53–0758	Main Street ramp	O/C	0.95	43	171	1950	n/a	No modification req'd.						
25	53–0627	Spring Street	O/C	1.01	128	70	1949	n/a	Remove existing O/C. Construct new O/C.	SF SF	128*70 158*70	8,960 11,060	20.00 80.00	179,200 884,800	
26	53–0811	Frontage road	O/C	1.02	64	32	1951	n/a	No modification req'd.						
27	53–0626	Broadway	O/C	1.08	128	60	1950	n/a	Remove existing O/C. Construct new O/C.	SF SF	128*60 158*60	7,680 9,480	20.00 80.00	153,600 758,400	
28	53–0090	Broadway on–ramp	O/C	1.10	40	60	1950	n/a	No modification req'd.						
29	53–0625	Hill Street	O/C	1.13	350	62	1951	n/a	Remove existing O/C. Construct new O/C.	SF SF	350*62 380*62	21,700 23,560	20.00 80.00	434,000 1,884,800	
30	53–0624	Grand Avenue	O/C	1.32	183	56	1948	n/a	Remove existing O/C. Construct new O/C.	SF SF	183*56 213*56	10,248 11,928	20.00 80.00	204,960 954,240	
Subtotal Page 3														7,618,300	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
31	53–0102–K	Temple Street ramp	O/C	1.40	126	24	1949	n/a	No modification req'd.						
32	53–0103–S	Grand Avenue ramp	O/C	1.42	213	24	1949	n/a	No modification req'd.						
33	53–0623–R	Figueroa Street	U/C	1.45	312	47	1949	n/a	Widen existing U/C.	SF	312*15	4,680	100.00	468,000	
34	53–0623–G	Figueroa Street	U/C	1.45	244	36	1949	n/a	No modification req'd.						
35	53–0623–L	Figueroa Street	U/C	1.45	314	47	1949	n/a	Widen existing U/C.	SF	314*15	4,710	100.00	471,000	
36	53–0622–R	Level 4 (of 4 level structure)	Connector	1.57	576	36	1949	n/a	No modification req'd.						
37	53–0622–L	Level 4 (of 4 level structure)	Connector	1.57	578	36	1949	n/a	No modification req'd.						
38	53–0622–F	Level 3 (of 4 level structure)	Connector	1.57	364	26	1949	n/a	No modification req'd.						
39	53–0622–G	Level 3 (of 4 level structure)	Connector	1.57	364	26	1949	n/a	No modification req'd.						
40	53–0240–H	Temple Street	U/C	1.63	97	37	1948	n/a	No modification req'd.						This structure is on Rt.110, not Rt.101???
Subtotal Page 4														939,000	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
41	53–0621	Beaudry Avenue	U/C	1.76	68	112	1949	n/a	Widen existing U/C.	SF	68*30	2,040	100.00	204,000	
42	53–0620	East Edgeware Road	O/C	2.07	126	40	1949	n/a	Remove existing O/C. Construct new O/C.	SF SF	126*40 156*40	5,040 6,240	20.00 80.00	100,800 499,200	
43	53–0689	Laveta Terrace	Ped. U/C	2.32	8	126	1950	n/a	Extend existing Pedestrian U/C.	SF	30*8	240	150.00	36,000	
44	53–0692	Echo Park	Ped. U/C	2.42	9	110	1950	n/a	Extend existing Pedestrian U/C.	SF	30*9	270	150.00	40,500	
45	53–0619	Glendale Boulevard	U/C	2.48	240	118	1950	n/a	Widen existing U/C.	SF	240*30	7,200	100.00	720,000	
46	53–0808	Belmont Avenue	Ped. O/C	2.60	185	n/a	1951	n/a	Remove existing Pedestrian O/C. Construct new Pedestrian O/C.	SF SF	185*10 215*10	1,850 2,150	20.00 100.00	37,000 215,000	
47	53–0618	Bonnie Brae Street	O/C	2.71	153	40	1949	n/a	Remove existing O/C. Construct new O/C.	SF SF	153*40 183*40	6,120 7,320	20.00 80.00	122,400 585,600	
48	53–0617	Alvarado Street (Route 2)	Separation (U/C)	2.86	113	162	1948	n/a	Widen existing separation.	SF	113*30	3,390	100.00	339,000	
49	53–0616	Rosemont Avenue	O/C	3.01	153	38	1949	n/a	Remove existing O/C. Construct new O/C.	SF SF	153*38 183*38	5,814 6,954	20.00 80.00	116,280 556,320	
50	53–0615	Coronado Street	U/C	3.20	136	128	1949	n/a	Widen existing U/C.	SF	136*30	4,080	100.00	408,000	
Subtotal Page 5														**3,980,100**	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
51	53–0614	Benton Way	O/C	3.34	148	40	1947	n/a	Remove existing O/C. Construct new O/C.	SF SF	148*40 178*40	5,920 7,120	20.00 80.00	118,400 569,600	
52	53–0690	Parkman Avenue	Ped. U/C	3.51	8	n/a	1950	n/a	Extend existing Pedestrian U/C.	SF	30*8	240	150.00	36,000	
53	53–0073	Vendome Street	U/C	3.63	136	134	1949	n/a	Widen existing U/C.	SF	136*30	4,080	100.00	408,000	
54	53–0613	Silverlake Boulevard	U/C	3.76	310	106	1948	n/a	Widen existing U/C.	SF	310*30	9,300	100.00	930,000	
55	53–0612	Hoover Street	U/C	3.94	177	127	1949	1963	Widen existing U/C.	SF	177*30	5,310	100.00	531,000	
56	53–0611–R	Virgil Avenue	U/C	4.08	178	50	1949	n/a	Widen existing U/C.	SF	178*15	2,670	100.00	267,000	
57	53–0611–L	Virgil Avenue	U/C	4.08	175	67	1949	1963	Widen existing U/C.	SF	175*15	2,625	100.00	262,500	
58	53–0609	Vermont Avenue	O/C	4.40	494	70	1949	n/a	Remove existing O/C. Construct new O/C.	SF SF	494*70 524*70	34,580 36,680	20.00 80.00	691,600 2,934,400	
59	53–0317–L	Clinton Street	U/C	4.58	824	50	1951	1982	Widen existing U/C.	SF	824*15	12,360	100.00	1,236,000	
60	53–0672–R	Heliotrope Drive	U/C	4.58	611	62	1950	n/a	Widen existing U/C.	SF	611*15	9,165	100.00	916,500	
Subtotal Page 6														**8,901,000**	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
61	53–0773–M	Kenmore Avenue Storm Drain	Box Culvert	4.73	27	72	1950	n/a	Extend existing box culvert.	SF	27*30	810	150.00	121,500	
62	53–0673–L	Melrose Avenue	U/C	4.85	245	50	1950	n/a	Widen existing U/C.	SF	245*15	3,675	100.00	367,500	
63	53–0673–R	Melrose Avenue	U/C	4.85	264	50	1950	n/a	Widen existing U/C.	SF	264*15	3,960	100.00	396,000	
64	53–0674	Normandie Avenue	U/C	4.99	219	112	1950	n/a	Widen existing U/C.	SF	219*30	6,570	100.00	657,000	
65	53–0691	Kingsley Avenue	Ped. U/C	5.17	7	n/a	1950	n/a	Extend existing Pedestrian U/C.	SF	30*7	210	150.00	31,500	
66	53–0675–W	Santa Monica Blvd Pump Plant	Pump Plant	5.54	n/a	n/a	1952	n/a	No modification req'd.						
67	53–0675	Santa Monica Blvd (Route 2)	Separation (O/C)	5.54	154	60	1950	n/a	Remove existing separation. Construct new separation.	SF SF	154*60 184*60	9,240 11,040	20.00 80.00	184,800 883,200	
68	53–0676	Western Avenue	O/C	5.81	242	60	1950	n/a	Remove existing O/C. Construct new O/C.	SF SF	242*60 272*60	14,520 16,320	20.00 80.00	290,400 1,305,600	
69	53–0984–W	St. Andrews Pump Plant	Pump Plant	5.90	n/a	n/a	1953	n/a	No modification req'd.						
70	53–0722	Fountain Avenue	O/C	5.94	264	48	1951	n/a	Remove existing O/C. Construct new O/C.	SF SF	264*48 294*48	12,672 14,112	20.00 80.00	253,440 1,128,960	
Subtotal Page 7														**5,619,900**	

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
71	53–0731	Wilton Place	O/C	6.15	341	40	1951	n/a	Remove existing O/C. Construct new O/C.	SF SF	341*40 371*40	13,640 14,840	20.00 80.00	272,800 1,187,200	
72	53–0677	Sunset Boulevard	O/C	6.25	168	75	1951	n/a	Remove existing O/C. Construct new O/C.	SF SF	168*75 198*75	12,600 14,850	20.00 80.00	252,000 1,188,000	
73	53–0732–K	Van Ness Avenue ramp	O/C (?)	6.41	317	32	1977	n/a	No modification req'd.						
74	53–0678	Hollywood Boulevard	O/C	6.52	194	84	1952	1977	Remove existing O/C. Construct new O/C.	SF SF	194*84 224*84	16,296 18,816	20.00 80.00	325,920 1,505,280	
75	53–0724	Bronson Avenue	O/C	6.65	259	54	1977	n/a	Remove existing O/C. Construct new O/C.	SF SF	259*54 289*54	13,986 15,606	20.00 80.00	279,720 1,248,480	
76	53–0679	Gower Street	U/C	6.91	164	143	1952	1977	Widen existing U/C.	SF	164*30	4,920	100.00	492,000	
77	53–0865–K	Gower Street off–ramp	U/C	7.04	292	24	1977	n/a	No modification req'd.						This structure separates the SB off–ramp from the SB on–ramp. Assume the freeway can be shifted to the north, so these ramps will remain on their current alignment.
78	53–0680	Argyle Avenue	U/C	7.06	602	138	1953	1977	Widen existing U/C.	SF	602*30	18,060	100.00	1,806,000	
79	53–0728–K	Franklin Avenue ramp	U/C	7.20	139	24	1953	n/a	No modification req'd.						
80	53–0797	Ivar Avenue	U/C	7.31	38	196	1953	1977	Widen existing U/C.	SF	38*30	1,140	100.00	114,000	
Subtotal Page 8														**8,671,400**	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
81	53–0783–K	Ivar Avenue ramp	Separation (??)	7.32	318	24	1953	1977	No modification req'd.						
82	53–0801	Holly Drive	U/C	7.38	41	169	1952	n/a	Widen existing U/C.	SF	41*30	1,230	100.00	123,000	
83	53–1782–S	Holly Drive ramp	U/C	7.40	66	32	1965	1977	No modification req'd.						
84	53–0681	Cahuenga Boulevard	U/C	7.46	150	150	1952	1977	Widen existing U/C.	SF	150*30	4,500	100.00	450,000	
85	53–0696	Odin Street	U/C	7.74	71	178	1954	1965	Widen existing U/C.	SF	71*30	2,130	100.00	213,000	
86	53–0729–L	Route 101/170	Separation (O/C)	7.84	449	60	1954	1977	Remove existing O/C. Construct new O/C.	SF SF	449*60 479*60	26,940 28,740	20.00 80.00	538,800 2,299,200	
87	53–0485–M	Pilgrimage Terrace	Ped. U/C	8.03	12	n/a	1940	1954	Extend existing Pedestrian U/C.	SF	30*12	360	150.00	54,000	
88	53–0468	Pilgrimage Terrace	O/C	8.05	212	26	1940	n/a	Remove existing O/C. Construct new O/C.	SF SF	212*26 242*26	5,512 6,292	20.00 80.00	110,240 503,360	
89	53–0989–K	Highland Avenue	Ped. U/C	8.15	10	24	1954	n/a	Extend existing Pedestrian U/C.	SF	30*10	300	150.00	45,000	
90	53–0866–K	Cahuenga Boulevard	U/C	8.25	386	24	1954	n/a	Widen existing U/C.	SF	386*30	11,580	100.00	1,158,000	
Subtotal Page 9														5,494,600	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 2	BRIDGE ESTIMATE	Route 101 – Hollywood Freeway in Los Angeles	07–LA–101–0.0/10.0

Item	Bridge Number	Name or Description	Structure Type	Post Mile	Existing Structure Length	Existing Structure Width	Year Built	Year Ext	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost	Comments
91	53–0301	Mulholland	O/C	8.75	282	26	1940	n/a	Remove existing O/C. Construct new O/C.	SF SF	282*26 312*26	7,332 8,112	20.00 80.00	146,640 648,960	
92	53–0551	Woodrow Wilson	Ped. U/C	8.82	8	209	1940	1957	Extend existing Pedestrian U/C.	SF	30*8	240	150.00	36,000	
93	53–0467	Oakcrest Drive	Ped. U/C	9.03	8	210	1940	n/a	Extend existing Pedestrian U/C.	SF	30*8	240	150.00	36,000	
94	53–0466	Barham Boulevard	O/C	9.22	167	48	1940	n/a	Remove existing O/C. Construct new O/C.	SF SF	167*48 197*48	8,016 9,456	20.00 80.00	160,320 756,480	
95	53–2712	Universal Drive	O/C	9.60	302	90	1983	n/a	Remove existing O/C. Construct new O/C.	SF SF	302*90 332*90	27,180 29,880	20.00 80.00	543,600 2,390,400	
Subtotal Page 10														**4,718,400**	

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3

07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	Mass Earthwork					8,283,333
02	Retaining Walls					21,600,000
03	Bridges					83,886,800
04	Pavement					14,755,680
05	Soundwalls					6,652,800
06	Landscaping and Erosion Control					1,000,000
07	Pedestrian and Bicycle Facilities					400,000
08	Signalization and Lighting					5,250,000
09	Drainage and Creek Channel Improvements					7,700,000
10	Barrier and Guard Railing					4,421,000
11	Signage					3,450,000
12	Striping					2,180,000
13	Construction Support and Detours					21,584,000
14	Existing Facilities – Remove, Salvage, Relocate, etc					10,450,000
15	Utility Relocation incl in Construction Contract					15,900,000
16	Other Itemized Costs					7,225,000
Subtotal						214,738,613
17	Mobilization				10.0%	21,473,861
Total Bid Level Cost						236,212,475
18	State Furnished Materials and Expenses					4,500,000
Subtotal						240,712,475
19	Contingency				20.0%	48,142,495
Total Construction Cost						288,854,970

20	Land Acquisition	67,690,000
21	Utility Relocation	27,250,000
Total Right-of-way Cost		94,940,000

Total Construction Cost plus Right-of-way Cost	383,794,970

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	**Mass Earthwork**					**8,283,333**
(a)	Assume average cross section of 30 ft width by 5 ft depth on both sides for 50% of project length.	CY	(0.5*10*5280*2*30*5)/27	293,333	10.00	2,933,333
(b)	Additional earthwork at reconfigured ramps. Assume 40 ramps with 1,500 CY per ramp.	CY	40*1500	60,000	10.00	600,000
(c)	Allowance for removal of contaminated soil.	CY		25,000	100.00	2,500,000
(d)	Allowance for additional mass earthwork at each of the nine AHS access locations.	CY	9*25000	225,000	10.00	2,250,000
02	**Retaining Walls**					**21,600,000**
(a)	Assume retaining walls are required for 25% of project length, with average height of 12 ft.	SF	0.25*10*5280*2*12	316,800	60.00	19,008,000
(b)	Allowance for additional retaining walls at each of the nine AHS access locations.	SF	9*400*12	43,200	60.00	2,592,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
03	**Bridges**					83,886,800
(a)	See the bridge estimate for option 2.	LS				65,877,200
	This item includes the cost of all vehicle, pedestrian, and railroad structures.					
	The cost also includes any required demolition of existing structures.					
(b)	Additional access ramp structures at each of the seven AHS access locations	SF	7*4*24*250	168,000	100.00	16,800,000
	involving overcrossings. These locations are the six listed in item (c) plus the					
	Sixth Street overcrossing.					
(c)	Additional length required at overcrossings to accommodate the AHS access					
	ramps:					
		SF	40*56	2,240	80.00	179,200
	1) Grand Avenue overcrossing	SF	40*70	2,800	80.00	224,000
	2) Vermont Avenue overcrossing	SF	40*60	2,400	80.00	192,000
	3) Santa Monica Blvd overcrossing	SF	40*84	3,360	80.00	268,800
	4) Hollywood Blvd overcrossing	SF	40*60	2,400	80.00	192,000
	5) Route 170 overcrossing	SF	40*48	1,920	80.00	153,600
	6) Barham Blvd overcrossing					

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
04	**Pavement**					**14,755,680**
(a)	Construct new travelled lanes.	SF	10*5280*2*12	1,267,200	4.00	5,068,800
(b)	Construct new outside shoulders.	SF	10*5280*2*10	1,056,000	2.50	2,640,000
(c)	Allowance for reconstruction of major local streets. Assume 10 each by 600 ft by 84 ft.	SF	10*600*84	504,000	3.00	1,512,000
(d)	Allowance for reconstruction of minor local streets. Assume 20 each by 500 ft by 50 ft.	SF	20*500*50	500,000	3.00	1,500,000
(e)	Allowance for reconstruction of ramps. Assume 40 each by 500 ft by 30 ft.	SF	40*500*30	600,000	3.00	1,800,000
(f)	Allowance for additional paving required due to revised profiles and alignments. Assume 10% of total cost of item 04(a).	LS	0.1*H90	506,880	1.00	506,880
(g)	Additional travelled lane pavement for auxiliary lanes at each of the nine AHS access locations.	SF	9*4*1000*12	432,000	4.00	1,728,000
05	**Soundwalls**					**6,652,800**
(a)	Assume soundwalls are required for 30% of project length, with average height of 14 ft.	SF	0.3*10*5280*2*14	443,520	15.00	6,652,800

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
06	**Landscaping and Erosion Control**					**1,000,000**
(a)	Assume the corridor is too narrow to accommodate mainline landscaping. Assume 2.0 acres of landscaping are required at each of 10 interchanges.	ACRE	2*10	20	50,000	1,000,000
07	**Pedestrian and Bicycle Facilities**					**400,000**
(a)	Pedestrian overcrossings and undercrossings are included with item 03–Bridges. Provide an additional allowance for facilities necessary to maintain pedestrian and bicycle access.	LS				250,000
(b)	Allowance for additional pedestrian and bicycle requirements due to interference from AHS access ramps on local streets.	LS				150,000
08	**Signalization and Lighting**					**5,250,000**
(a)	Assume major signalization and lighting modifications are required at 20 locations. Assume that most of the existing equipment can be salvaged and re–used.	EA		20	150,000	3,000,000
(b)	Additional signalization and lighting required at each of the nine AHS access locations.	EA		9	250,000	2,250,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
09	**Drainage and Creek Channel Improvements**					7,700,000
(a)	Assume no major work is required at the Los Angeles River or at other creek crossings. Assume no major modifications are required to longitudinal drainage or interceptors. Provide an allowance for freeway drainage.	MILE		10	500,000	5,000,000
(b)	Additional drainage required at each of the nine AHS access locations.	EA		9	300,000	2,700,000
10	**Barrier and Guard Railing**					4,421,000
(a)	There is an existing concrete or metal beam barrier in the freeway median for essentially the total length of the corridor. Assume 25% of this barrier will need to be replaced due to realignments, profile changes, etc.	LF	0.25*10*5280	13,200	40.00	528,000
(b)	Allowance for additional barrier or guard railing required on the outside shoulders. Assume 25% of the total freeway length.	LF	0.25*2*10*5280	26,400	40.00	1,056,000
(c)	Allowance for additional barrier or guard railing required at ramps and local streets.	LS				500,000
(d)	Additional barrier and guard railing required at each of the nine AHS access locations.	EA		9	25,000	225,000
(e)	Continuous concrete barrier separating AHS lane from conventional traffic lane.	LF	2*10*5280	105,600	20.00	2,112,000
11	**Signage**					3,450,000
(a)	Allowance.	MILE		10	300,000	3,000,000
(b)	Additional signage required at each of the nine AHS access locations.	EA		9	50,000	450,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
12	**Striping**					2,180,000
(a)	Allowance.	MILE		10	200,000	2,000,000
(b)	Additional striping required at each of the nine AHS access locations.	EA		9	20,000	180,000
13	**Construction Support and Detours**					21,584,000
(a)	Detours and other temporary construction.	LS				5,000,000
(b)	Temporary signage, striping, lighting, etc.	LS				2,000,000
(c)	Traffic control during construction.	LS				5,000,000
(d)	Temporary railing (Type K) – Assume full length of corridor on both sides. Add 25% for interchanges and local streets.	LF	10*5280*2*1.25	132,000	12.00	1,584,000
(e)	Construction staking.	LS				2,000,000
(f)	Develop water supply.	LS				500,000
(g)	Contractor is required to provide a monthly critical path schedule update. This is a contract bid item.	LS				500,000
(h)	Other misc construction support costs.	LS				500,000
(i)	Additional construction support (includes items "a" thru "h") required at each of the nine AHS access locations.	EA		9	500,000	4,500,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
14	**Existing Facilities – Remove, Salvage, Relocate, etc**					**10,450,000**
(a)	Allowance for removal, salvage, relocation, etc of minor items such as sidewalks, guardrails, signs, drainage structures, etc.	LS				10,000,000
	This cost excludes the removal of existing bridge structures, which are included in item 03–Bridges.					
(b)	Additional work required at each of the nine AHS access locations.	EA		9	50,000	450,000
15	**Utility Relocation incl in Construction Contract**					**15,900,000**
(a)	Allowance for utility relocations to be performed by state's contractor. This will include primarily local sewer and water lines.	LS				15,000,000
(b)	Additional utility relocations required at each of the nine AHS access locations.	EA		9	100,000	900,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
16	**Other Itemized Costs**					7,225,000
(a)	Allowance for other costs, including: Minor concrete (curb, gutter, sidewalk, etc.). Fencing and gates. Survey monuments.	LS				5,000,000
(b)	Furnish and install AHS magnets. Assume purchase cost of magnets is $1.00 each. Assume magnets are 4.0 inches long, 1.0 inch diameter, 2.0 inches deep, and spaced at an interval of 3.0 feet.	EA	(2*10*5280)/3	35,200	25.00	880,000
(c)	Additional AHS magnets in access ramps.	EA	(9*4*1250)/3	15,000	25.00	375,000
(d)	Furnish and install 20 ft poles for video coverage. Assume one line of poles in the median, spaced at 165 ft (32 per mile). Include hookup to power and phone lines. Exclude video equipment.	EA	10*5280/165	320	2,500	800,000
(e)	Install Local Control Center (LCC). LCC's are required at 5 mile intervals.	EA	10/5	2	10,000	20,000
(f)	Install Master Control Center (MCC). MCC's are required at 50 mile intervals. Assume MCC will be located in an existing state–owned facility, so no land acquisition is required. Assume facility is a habitable building about 1,000 square feet, incorporating a relatively high level of security measures.	EA		1	100,000	100,000
(g)	Install equipment rack at on–ramps. Assume installation requirements will be similar to a signal controler.	EA	2*10	20	2,500	50,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 3	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
18	**State Furnished Materials and Expenses**					**4,500,000**
(a)	Resident engineer's office.	LS				1,500,000
(b)	Sign panels.	LS				1,000,000
(c)	Traffic signal controllers.	LS				1,000,000
(d)	Other misc items.	LS				500,000
(e)	Additional cost for AHS access locations.	LS				500,000
20	**Land Acquisition**					**67,690,000**
(a)	Assume an average width of 30 ft must be acquired for the entire length of the corridor.	SF	10*5280*30	1,584,000	25.00	39,600,000
(b)	Assume an additional 1.0 acre will be required at each of 10 interchange areas.	SF	10*1*43560	435,600	25.00	10,890,000
(c)	Allowance for preservation or relocation of historical, archaeological, or cultural resources.	LS				1,000,000
(d)	Additional right–of–way width required at AHS access locations.	SF	9*24*3000	648,000	25.00	16,200,000
21	**Utility Relocation**					**27,250,000**
(a)	Allowance for major utility relocations to be performed by the utility companies or their contractors (excl. railroads).	LS				20,000,000
(b)	Allowance for railroad relocations or modifications to be performed by the railroad companies or their contractors.	LS				5,000,000
(c)	Additional utility relocations required at each of the nine AHS access locations.	EA		9	250,000	2,250,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	Mass Earthwork					0
02	Retaining Walls					0
03	Bridges					0
04	Pavement					0
05	Soundwalls					0
06	Landscaping and Erosion Control					0
07	Pedestrian and Bicycle Facilities					0
08	Signalization and Lighting					0
09	Drainage and Creek Channel Improvements					0
10	Barrier and Guard Railing					0
11	Signage					150,000
12	Striping					528,000
13	Construction Support and Detours					1,120,000
14	Existing Facilities – Remove, Salvage, Relocate, etc					0
15	Utility Relocation incl in Construction Contract					0
16	Other Itemized Costs					1,850,000
Subtotal						3,648,000
17	Mobilization				10.0%	364,800
Total Bid Level Cost						4,012,800
18	State Furnished Materials and Expenses					50,000
Subtotal						4,062,800
19	Contingency				20.0%	812,560
Total Construction Cost						4,875,360

20	Land Acquisition	0
21	Utility Relocation	0
Total Right–of–way Cost		0

Total Construction Cost plus Right–of–way Cost	4,875,360

IVHS\SUM4A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	**Mass Earthwork**					**0**
(a)	No mass earthwork required.	---	---	---	---	0
02	**Retaining Walls**					**0**
(a)	No retaining walls required.	---	---	---	---	0
03	**Bridges**					**0**
(a)	No bridges required.	---	---	---	---	0

IVHS\SUM4A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
04	**Pavement**					0
(a)	No pavement required.	---	---	---	---	0
05	**Soundwalls**					0
(a)	No soundwalls required.	---	---	---	---	0

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
06	**Landscaping and Erosion Control**					**0**
(a)	No landscaping and erosion control required.	---	---	---	---	0
07	**Pedestrian and Bicycle Facilities**					**0**
(a)	No pedestrian and bicycle facilities required.	---	---	---	---	0
08	**Signalization and Lighting**					**0**
(a)	No signalization and lighting required.	---	---	---	---	0

IVHS\SUM4A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
09	**Drainage and Creek Channel Improvements**					**0**
(a)	No drainage and creek channel improvements required.	---	---	---	---	0
10	**Barrier and Guard Railing**					**0**
(a)	No barrier and guard railing required.	---	---	---	---	0
11	**Signage**					**150,000**
(a)	Allowance for signage.	MILE		10	15,000	150,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
12	**Striping**					528,000
(a)	Rumble strip separating the AHS lane from the conventional lanes.	LF	2*10*5280	105,600	5.00	528,000
13	**Construction Support and Detours**					1,120,000
(a)	Detours and other temporary construction. Not required.	---	---	---	---	0
(b)	Temporary signage, striping, lighting, etc. Not required.	---	---	---	---	0
(c)	Traffic control during construction.	LS				1,000,000
(d)	Temporary railing (Type K) – Not required.	---	---	---	---	0
(e)	Construction staking. Not required.	---	---	---	---	0
(f)	Develop water supply. Not required.	---	---	---	---	0
(g)	Contractor is required to provide a monthly critical path schedule update. This is a contract bid item.	LS				20,000
(h)	Other misc construction support costs.	LS				100,000

IVHS\SUM4A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4 | **07–LA–101–0.0/10.0**

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
14	**Existing Facilities – Remove, Salvage, Relocate, etc**					**0**
(a)	No work required.	---	---	---	---	0
15	**Utility Relocation incl in Construction Contract**					**0**
(a)	No utility relocation required.	---	---	---	---	0
16	**Other Itemized Costs**					**1,850,000**
(a)	Allowance for other costs. Not required.	---	---	---	---	0
(b)	Furnish and install A.H.S. magnets. Assume purchase cost of magnets is $1.00 each. Assume magnets are 4.0 inches long, 1.0 inch diameter, 2.0 inches deep, and spaced at an interval of 3.0 feet.	EA	(2*10*5280)/3	35,200	25.00	880,000
(c)	Furnish and install 20 ft poles for video coverage. Assume one line of poles in the median, spaced at 165 ft (32 per mile). Include hookup to power and phone lines. Exclude video equipment.	EA	10*5280/165	320	2,500	800,000
(d)	Install Local Control Center (LCC). LCC's are required at 5 mile intervals.	EA	10/5	2	10,000	20,000
(e)	Install Master Control Center (MCC). MCC's are required at 50 mile intervals. Assume MCC will be located in a existing state–owned facility, so no land acquisition is required. Assume facility is a habitable building about 1,000 square feet, incorporating a relatively high level of security measures.	EA		1	100,000	100,000
(f)	Install equipment rack at on–ramps. Assume installation requirements will be similar to a signal controller.	EA	2*10	20	2,500	50,000

IVHS\SUM4A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 4	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
18	**State Furnished Materials and Expenses**					**50,000**
(a)	Resident engineer's office. Not required.	LS				0
(b)	Sign panels. Not required.	LS				0
(c)	Traffic signal controllers. Not required.	---	---	---	---	0
(d)	Other misc items.	LS				50,000
20	**Land Acquisition**					**0**
(a)	No land acquisition required.	---	---	---	---	0
21	**Utility Relocation**					**0**
(a)	No utility relocation required.	---	---	---	---	0

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	Mass Earthwork					5,000,000
02	Retaining Walls					5,184,000
03	Bridges					149,320,000
04	Pavement					215,200
05	Soundwalls					0
06	Landscaping and Erosion Control					0
07	Pedestrian and Bicycle Facilities					100,000
08	Signalization and Lighting					2,250,000
09	Drainage and Creek Channel Improvements					2,250,000
10	Barrier and Guard Railing					225,000
11	Signage					450,000
12	Striping					380,000
13	Construction Support and Detours					21,584,000
14	Existing Facilities – Remove, Salvage, Relocate, etc					5,000,000
15	Utility Relocation incl in Construction Contract					5,000
16	Other Itemized Costs					4,225,000
Subtotal						196,188,200
17	Mobilization				10.0%	19,618,820
Total Bid Level Cost						215,807,020
18	State Furnished Materials and Expenses					4,000,000
Subtotal						219,807,020
19	Contingency				20.0%	43,961,404
Total Construction Cost						263,768,424

20	Land Acquisition	16,200,000
21	Utility Relocation	2,250,000
Total Right–of–way Cost		18,450,000

Total Construction Cost plus Right–of–way Cost	282,218,424

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
01	**Mass Earthwork**					**5,000,000**
(a)	Allowance for additional mass earthwork at each of the nine AHS access locations.	CY	9*50000	450,000	10.00	4,500,000
(b)	Allowance for removal of contaminated soil.	CY		5,000	100.00	500,000
02	**Retaining Walls**					**5,184,000**
(a)	Allowance for additional retaining walls at each of the nine AHS access locations.	SF	9*800*12	86,400	60.00	5,184,000

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
03	**Bridges**					149,320,000
(a)	Assume all existing bridge structures will remain as–is.	LS				0
(b)	Elevated AHS viaduct for entire length of corridor.	SF	10*5280*40	2,112,000	60.00	126,720,000
(c)	Additional access ramp structures at each of the nine AHS access locations.	SF	9*4*24*250	216,000	100.00	21,600,000
(d)	Additional cost to accommodate columns for elevated AHS viaduct in the existing median.	MI		10	100,000	1,000,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
04	**Pavement**					**215,200**
(a)	Pavement required at the conform to the local street at each of the two AHS access locations involving undercrossings.	SF	2*4*24*200	38,400	3.00	115,200
(b)	Allowance for misc paving at other areas.	LS				100,000
05	**Soundwalls**					**0**
(a)	Assume soundwalls will not be required.	LS				0

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
06	**Landscaping and Erosion Control**					**0**
(a)	Assume landscaping will not be required.	LS				0
07	**Pedestrian and Bicycle Facilities**					**100,000**
(a)	Allowance for additional pedestrian and bicycle requirements due to interference from AHS access ramps on local streets.	LS				100,000
08	**Signalization and Lighting**					**2,250,000**
(a)	Additional signalization and lighting required at each of the nine AHS access locations.	EA		9	250,000	2,250,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
09	**Drainage and Creek Channel Improvements**					2,250,000
(a)	Additional drainage required at each of the nine AHS access locations.	EA		9	250,000	2,250,000
10	**Barrier and Guard Railing**					225,000
(a)	Additional barrier and guard railing required at each of the nine AHS access locations.	EA		9	25,000	225,000
11	**Signage**					450,000
(a)	Additional signage required at each of the nine AHS access locations.	EA		9	50,000	450,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
12	**Striping**					380,000
(a)	Additional striping required at each of the nine AHS access locations.	EA		9	20,000	180,000
(b)	Striping on AHS structure.	MI		10	20,000	200,000
13	**Construction Support and Detours**					21,584,000
(a)	Detours and other temporary construction.	LS				5,000,000
(b)	Temporary signage, striping, lighting, etc.	LS				2,000,000
(c)	Traffic control during construction.	LS				5,000,000
(d)	Temporary railing (Type K) – Assume full length of corridor on both sides. Add 25% for interchanges and local streets.	LF	10*5280*2*1.25	132,000	12.00	1,584,000
(e)	Construction staking.	LS				2,000,000
(f)	Develop water supply.	LS				500,000
(g)	Contractor is required to provide a monthly critical path schedule update. This is a contract bid item.	LS				500,000
(h)	Other misc construction support costs.	LS				500,000
(i)	Additional construction support required at each of the nine AHS access locations.	EA		9	500,000	4,500,000

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AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5						07–LA–101–0.0/10.0
Item	**Description**	**Unit**	**Calculation**	**Quantity**	**Unit Cost**	**Total Cost**
14	**Existing Facilities – Remove, Salvage, Relocate, etc**					**5,000,000**
(a)	Allowance for removal, salvage, relocation, etc of minor items such as sidewalks, guardrails, signs, drainage structures, etc.	LS				5,000,000
15	**Utility Relocation incl in Construction Contract**					**5,000**
(a)	Allowance for utility relocations to be performed by state's contractor. This will include primarily local sewer and water lines.	LS				5,000

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
16	**Other Itemized Costs**					4,225,000
(a)	Allowance for other costs, including: Minor concrete (curb, gutter, sidewalk, etc.). Fencing and gates. Survey monuments.	LS				2,000,000
(b)	Furnish and install AHS magnets. Assume purchase cost of magnets is $1.00 each. Assume magnets are 4.0 inches long, 1.0 inch diameter, 2.0 inches deep, and spaced at an interval of 3.0 feet.	EA	(2*10*5280)/3	35,200	25.00	880,000
(c)	Additional AHS magnets in access ramps.	EA	(9*4*1250)/3	15,000	25.00	375,000
(d)	Furnish and install 20 ft poles for video coverage. Assume one line of poles in the median, spaced at 165 ft (32 per mile). Include hookup to power and phone lines. Exclude video equipment.	EA	10*5280/165	320	2,500	800,000
(e)	Install Local Control Center (LCC). LCC's are required at 5 mile intervals.	EA	10/5	2	10,000	20,000
(f)	Install Master Control Center (MCC). MCC's are required at 50 mile intervals. Assume MCC will be located in an existing state–owned facility, so no land acquisition is required. Assume facility is a habitable building about 1,000 square feet, incorporating a relatively high level of security measures.	EA		1	100,000	100,000
(e)	Install equipment rack at on–ramps. Assume installation requirements will be similar to a signal controller.	EA	2*10	20	2,500	50,000

IVHS\SUM5A

AUTOMATED HIGHWAY SYSTEM – RETROFIT OPTION 5	07–LA–101–0.0/10.0

Item	Description	Unit	Calculation	Quantity	Unit Cost	Total Cost
18	**State Furnished Materials and Expenses**					4,000,000
(a)	Resident engineer's office.	LS				1,500,000
(b)	Sign panels.	LS				1,000,000
(c)	Traffic signal controllers.	LS				1,000,000
(d)	Other misc items.	LS				500,000
20	**Land Acquisition**					16,200,000
(a)	Additional right–of–way width required at AHS access locations.	SF	9*24*3000	648,000	25.00	16,200,000
21	**Utility Relocation**					2,250,000
(a)	Additional utility relocations required at each of the nine AHS access locations.	EA		9	250,000	2,250,000

Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Analysis of automated Highway System Risks and Uncertainies

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-159
March 1995

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

ABSTRACT

This volume describes a risk analysis performed to help identify important Automated Highway System (AHS) deployment uncertainties and quantify their effect on costs and benefits for a range of AHS deployment scenarios. The analysis identified a suite of key factors affecting vehicle and roadway costs, capacities and market penetrations for alternative AHS deployment scenarios. A systematic protocol was utilized for obtaining expert judgments of key factor uncertainties in the form of subjective probability percentile assessments. Based on these assessments, probability distributions on vehicle and roadway costs, capacity and market penetration were developed for the different scenarios. The cost/benefit risk methodology and analysis provide insights by showing how uncertainties in key factors translate into uncertainties in summary cost/benefit indices.

ANALYSIS OF AUTOMATED HIGHWAY SYSTEM RISKS AND UNCERTAINTIES
Vol. V

for
Federal Highway Administration
Precursor Systems Analysis of Automated Highway Systems
Activity Area p: Preliminary Cost/Benefit Factors Analysis

October, 1994

Alan Sicherman
Lawrence Livermore National Laboratory

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1. INTRODUCTION

This volume describes the "risk" analysis performed to help identify important Automated Highway System (AHS) deployment uncertainties and quantify their effect on costs and benefits for a range of AHS deployment scenarios. The cost/benefit risk analysis shows more formally how uncertainties in key implementation assumptions translate into uncertainties in summary cost/benefit indices. Although approximate, the risk analysis can provide planners with basic insights about the likelihood of realizing possible implementation cost and market penetration levels for alternative AHS deployment scenarios. These insights can also help direct further research efforts aimed at reducing the more acute uncertainties.

Specific Focus of Effort

Many types of uncertainties associated with requirements for successful AHS deployment have been identified.[1] These requirements include technological feasibility, institutional and interest group acceptance, willingness of auto makers to manufacture the required equipment, and willingness of customers to buy and maintain AHS equipped vehicles. In the volumes of this study, no attempt has been made to estimate the feasibility uncertainties of implementing AHS at either the technical or institutional level. Instead, the costs and benefits of alternative AHS scenarios have been analyzed under the assumption that system configurations perform as anticipated.

A key product of this study has been the creation of original AHS scenario cost estimates. These estimates for electronics costs and roadway infrastructure costs are developed in volumes 3 and 4 of this report for various deployment scenarios. However, each of the cost estimates developed is in the form of a single summary number or *best guess*. The risk analysis described in this volume develops *probability distributions* for the costs of each scenario. Unlike a single number or point estimate, these probability distributions quantify the range of uncertainty associated with scenario costs. The distributions specify the *risk* or likelihood that costs could turn out to be significantly higher (or lower) than estimated. The risk analysis shows how each scenario cost uncertainty range relates to the uncertainties in key cost estimation input parameters. In this way, the analysis helps to identify which parameters are most important to study further if reduction in uncertainty and risk is to be achieved. Besides costs, probability distributions are also developed for capacity gains and market penetration for selected scenarios.

Risk Analysis Overall Approach

The risk analysis was performed in four steps. These are outlined below.

Step 1: Selection of key cost/benefit factors for uncertainty assessment. Before costs and benefits of an AHS can be assessed, different AHS deployment scenarios are specified. Then models/judgments are used to quantify various kinds of costs and benefits that ensue given a specific AHS scenario.

In this step, key quantitative factors affecting the cost/benefits of particular AHS deployment scenarios were selected. The factors were chosen to be:

- comprehensive enough to address issues about which there may be significant uncertainty and/or concern.
- well-defined and meaningful to project team specialists.
- practical for addressing a variety of deployment scenarios.
- relatively few in number to make the overall analysis tractable.

In addition to *bottom-line* summary cost/benefit factors, we identified key “intermediate” parameters related to them which needed to be explicitly considered.

Step 2: Percentile estimates assessment for key factors. Percentile estimates for each key factor/parameter were assessed from individual specialists on the project team using formal subjective probability assessment techniques. In addition to formalizing parameter uncertainties quantitatively, these techniques help prevent the common pitfall of understating the uncertainty in knowledge that is present about key parameters. The estimates obtained were used to develop three-point probability (uncertainty) distribution approximations for each key parameter.

Activities in this step included implementing a formal interview protocol so that the assessment techniques were applied consistently and systematically for each factor. Assessments were conducted to exploit the common variables underlying different deployment scenarios and thus streamline the nature and number of assessments performed. Priority was placed on assessing factors that were intuitively felt to have the most significant uncertainty and greatest impact on cost/benefit results.

Step 3: Development of a simplified framework delineating relationships among intermediate and summary cost/benefit factors. This step developed formulas relating the intermediate parameters and *summary* cost/benefit factors with each other for each AHS scenario considered. The framework utilized the assessments and three-point distributions described in Step 2 as input to develop probability distributions on overall *bottom-line* cost/benefits.

Step 4: Framework implementation and risk analysis results. The framework from Step 3 was implemented on spreadsheet software for a personal computer. Tables and graphs of sensitivity analyses and probability distribution outputs were generated to highlight the likelihood of various cost/benefit results ensuing from different options. These results provide additional insight beyond that from using a *best guess* type (i.e., single point) estimate for each parameter, or from simplistic bounds obtained by using extremely optimistic or pessimistic estimates for all parameters. The risk analysis helps indicate which factors and uncertainties are most significant in influencing the relative desirability of an AHS option. While the modeling is of necessity approximate, basic insights obtained should help planners make projections of how likely it will be to realize various levels of costs and benefits from implementing an AHS.

Report Organization

The remainder of this report is organized as follows. Sections 2 through 5 describe each of the four steps of the risk analysis approach in more detail. section 6 presents conclusions and recommendations for further study. The appendix contains formula details related to step 3 of the risk analysis approach.

2. SELECTION OF KEY COST/BENEFIT FACTORS FOR UNCERTAINTY ASSESSMENT

This section lists the various vehicle modification and roadway retrofit options considered by the risk analysis in defining alternative AHS implementation scenarios. Then, the factors selected for assessing scenario cost/benefit uncertainties are listed and discussed.

A list of factors was developed and organized into a structure for assessing cost/benefit uncertainties (see figure 1). The structure in figure 1 is discussed below.

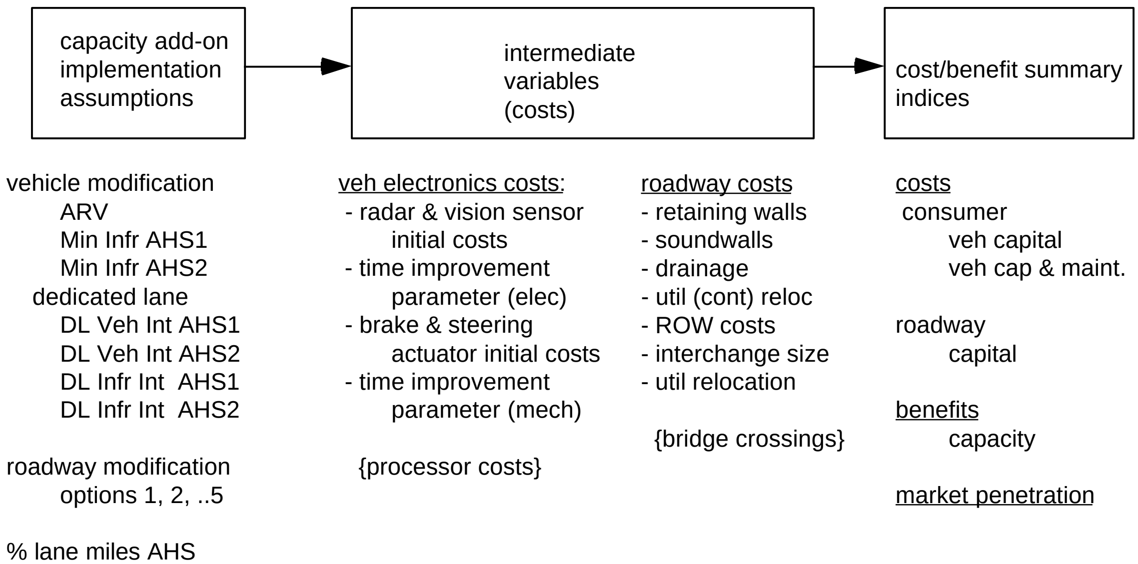


Figure 1. AHS options risk analysis: structure of factors for probability assessments.

Implementation Context Assumptions

Specific choices of roadway modification and vehicle modification assumptions define an AHS implementation scenario context. Cost and benefit estimates are different and calculated separately for each scenario. The vehicle modifications considered in the risk analysis are the seven vehicle options analyzed in volume 3. The roadway modifications considered are the five retrofit options analyzed in volume 4. Finally, assumptions about the percentage of freeway lane kilometers adapted for AHS relate to defining market penetration scenarios.

Basic vehicle types are the AHS ready vehicle (ARV), a fully automated vehicle but not able to automatically change lanes (AHS1), and a fully automated vehicle able to change lanes under full automation (AHS2). The seven vehicle modification options listed in figure 1 are very briefly summarized as follows (see volume 3 for more detail):

- ARV.
- AHS1 vehicle operating in mixed traffic with minimum infrastructure modification (Min Infr AHS1).
- AHS2 vehicle operating in mixed traffic with minimum infrastructure modification. (Min Infr AHS2).
- AHS1 vehicle operating on a dedicated AHS lane with vehicle intensive placement of sensing capabilities (DL Veh Int AHS1).
- AHS2 vehicle operating on a dedicated AHS lane with vehicle intensive placement of sensing capabilities (DL Veh Int AHS2).
- AHS1 vehicle operating on a dedicated AHS lane with more infrastructure intensive placement of sensing capabilities (DL Infr Int AHS1).
- AHS2 vehicle operating on a dedicated AHS lane with more infrastructure intensive placement of sensing capabilities (DL Infr Int AHS2).

The five roadway modification options are very briefly summarized as follows (see volume 4 for more detail):

- Option 1: all existing lanes remain but are automated.
- Option 2: one lane automated - three lanes conventional, buffer lane added between automated and conventional lane.
- Option 3: similar to Option 2 without buffer, on/off ramps added with bridge structure.
- Option 4: one lane automated, three lanes to remain conventional, separation by wide striping or rumble strips.
- Option 5: dedicated AHS structure - elevated.

Intermediate Variables

In the Electronics Cost Methodology (volume 3) and Roadway Infrastructure Cost Methodology (volume 4), models are described in which single number or point estimates are used for model parameters to compute summary costs for vehicle acquisition and maintenance, and roadway construction costs respectively for the different options under consideration. Tables 1 and 2 recap summaries of these model inputs and computations that were available at the time this risk analysis was performed. (*Note*: results in volumes 3 and 4 may differ from these tables reflecting changes to these computations that were made subsequent to this risk analysis. The risk analysis methodology and basic insights, however, should still be relevant.)

Table 1. Vehicle costs summary (point estimates).

Electronics procurement cost per vehicle, 2002 procurement, 1994 dollars, 1million unit market

E - Electronics component
M - Electro-mechanical component

					Dedicated Lanes			
			Mixed Traffic		Vehicle Intensive		Infrastructure Intensive	
		ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
	VEHICLE	$1,045	$1,604	$1,905	$1,464	$1,742	$1,514	$1,672
SENSORS		$366	$584	$776	$570	$762	$570	$762
E	MULTI BEAM MILLIMETER RADAR	$306	$306	$306	$306	$306	$306	$306
E	MAGNETIC FIELD SENSOR	$60	$60	$0	$60	$0	$60	$0
E	VISION-BASED SENSOR	$0	$180	$360	$90	$270	$90	$270
M	RAIN/SNOW SENSOR	$0	$38	$38	$38	$38	$0	$0
M	BEACON EMITTERS	$0	$0	$0	$76	$76	$114	$114
E	MAG FIELD SENSOR W/ CODE	$0	$0	$72	$0	$72	$0	$72
INTELLIGENCE		$103	$481	$590	$355	$441	$332	$298
E	PROCESSOR/DIAGNOSTICS (1)	$103	$0	$0	$0	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (3.4)	$0	$0	$0	$0	$0	$0	$298
E	PROCESSOR/DIAGNOSTICS (4.0)	$0	$0	$0	$0	$0	$332	$0
E	PROCESSOR/DIAGNOSTICS (4.4)	$0	$0	$0	$355	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (5.9)	$0	$0	$0	$0	$441	$0	$0
E	PROCESSOR/DIAGNOSTICS (6.6)	$0	$481	$0	$0	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (8.5)	$0	$0	$590	$0	$0	$0	$0
COMMUNICATION		$0	$58	$58	$58	$58	$131	$131
E	ROAD TO VEHICLE (TMS), Receive	$0	$10	$10	$10	$10	$0	$0
E	VEHICLE/VEHICLE, FORE & AFT	$0	$48	$48	$48	$48	$48	$48
E	R/T, AUTO CHECK-IN AND CONTROL	$0	$0	$0	$0	$0	$83	$83
ACTUATORS		$513	$361	$361	$361	$361	$361	$361
M	BRAKE ACTUATOR	$190	$190	$190	$190	$190	$190	$190
M	THROTTLE ACTUATOR (Engine Control)	$19	$19	$19	$19	$19	$19	$19
M	STEERING ACTUATOR	$304	$304	$304	$304	$304	$304	$304
M	(LESS STD DIRECT DRIVE)	$0	($152)	($152)	($152)	($152)	($152)	($152)
INTERFACES		$63	$120	$120	$120	$120	$120	$120
E	STD ACTUATOR INTERFACE UNIT	$6	$6	$6	$6	$6	$6	$6
M	DRIVER INTERFACE UNIT	$57	$0	$0	$0	$0	$0	$0
M	DRIVE BY WIRE DRIVER INT UNIT	$0	$114	$114	$114	$114	$114	$114
v1	Brake & steering actuator	$494	$494	$494	$494	$494	$494	$494
v2	Radar & vision sensor (PRICE components)	$306	$486	$666	$396	$576	$396	$576
v3	Other electronics	$169	$605	$726	$479	$577	$529	$507
v4	Other electro-mechanical	$76	$19	$19	$95	$95	$95	$95

Table 1 (continued). Vehicle costs summary (point estimates).

Electronics 7 yr support cost per vehicle, 2002 procurement, 1994 dollars, 1million unit market

E - Electronics component
M - Electro-mechanical component

					Dedicated Lanes			
			Mixed Traffic		Vehicle Intensive		Infrastructure Intensive	
		ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
	VEHICLE	$571	$1,134	$1,399	$913	$1,106	$904	$922
SENSORS		$164	$221	$284	$197	$260	$198	$261
E	MULTI BEAM MILLIMETER RADAR	$142	$142	$142	$142	$142	$142	$142
E	MAGNETIC FIELD SENSOR	$22	$22	$0	$22	$0	$22	$0
E	VISION-BASED SENSOR	$0	$56	$112	$28	$84	$28	$84
M	RAIN/SNOW SENSOR	$0	$1	$1	$1	$1	$0	$0
M	BEACON EMITTERS	$0	$0	$0	$4	$4	$6	$6
E	MAG FIELD SENSOR W/ CODE	$0	$0	$29	$0	$29	$0	$29
INTELLIGENCE		$91	$565	$767	$368	$498	$336	$291
E	PROCESSOR/DIAGNOSTICS (1)	$91	$0	$0	$0	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (3.4)	$0	$0	$0	$0	$0	$0	$291
E	PROCESSOR/DIAGNOSTICS (4.0)	$0	$0	$0	$0	$0	$336	$0
E	PROCESSOR/DIAGNOSTICS (4.4)	$0	$0	$0	$368	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (5.9)	$0	$0	$0	$0	$498	$0	$0
E	PROCESSOR/DIAGNOSTICS (6.6)	$0	$565	$0	$0	$0	$0	$0
E	PROCESSOR/DIAGNOSTICS (8.5)	$0	$0	$767	$0	$0	$0	$0
COMMUNICATION		$0	$5	$5	$5	$5	$27	$27
E	ROAD TO VEHICLE (TMS), Receive	$0	$0	$0	$0	$0	$0	$0
E	VEHICLE/VEHICLE, FORE & AFT	$0	$5	$5	$5	$5	$5	$5
E	R/T, AUTO CHECK-IN AND CONTROL	$0	$0	$0	$0	$0	$22	$22
ACTUATORS		$311	$311	$311	$311	$311	$311	$311
M	BRAKE ACTUATOR	$107	$107	$107	$107	$107	$107	$107
M	THROTTLE ACTUATOR (Engine Control)	$5	$5	$5	$5	$5	$5	$5
M	STEERING ACTUATOR	$199	$199	$199	$199	$199	$199	$199
M	(LESS STD DIRECT DRIVE)	$0	$0	$0	$0	$0	$0	$0
INTERFACES		$5	$32	$32	$32	$32	$32	$32
E	STD ACTUATOR INTERFACE UNIT	$4	$4	$4	$4	$4	$4	$4
M	DRIVER INTERFACE UNIT	$1	$0	$0	$0	$0	$0	$0
M	DRIVE BY WIRE DRIVER INT UNIT	$0	$28	$28	$28	$28	$28	$28
vm1	Total electronics	$259	$794	$1,059	$569	$762	$559	$577
vm2	Total electro-mechanical	$312	$340	$340	$344	$344	$345	$345

Table 2. Roadway costs summary (point estimates).

Roadway construction cost estimates

Item	Description	Option 2	Option 3	Option 5	Option 1	Option 4
1	Mass Earthwork	6,033,333	8,283,333	5,000,000	0	0
2	Retaining Walls	19,008,000	21,600,000	5,184,000	0	0
3	Bridges	65,877,200	83,886,800	148,320,000	0	0
4	Pavement	13,027,680	14,755,680	215,200	0	0
5	Soundwalls	6,652,800	6,652,800	0	0	0
6	Landscaping and Erosion Control	1,000,000	1,000,000	0	0	0
7	Pedestrian and Bicycle Facilities	250,000	400,000	100,000	0	0
8	Signalization and Lighting	3,000,000	5,250,000	2,250,000	0	0
9	Drainage & Creek Channel Improvements	5,000,000	7,700,000	2,250,000	0	0
10	Barrier and Guard Railing	2,084,000	2,309,000	225,000	0	0
11	Signage	3,000,000	3,450,000	450,000	150,000	150,000
12	Striping	2,000,000	2,180,000	380,000	0	528,000
13	Construction Support and Detours	17,084,000	21,584,000	21,584,000	2,220,000	1,120,000
14	Existing Facilities - Remove, salvage, etc	10,000,000	10,450,000	5,000,000	0	0
15	Utility Relocation incl in Construction Contract	15,000,000	15,900,000	5,000	0	0
16	Other Itemized Costs	5,880,000	6,255,000	3,255,000	3,520,000	880,000
	Subtotal	**174,897,013**	**211,656,613**	**194,218,200**	**5,890,000**	**2,678,000**
17	Mobilization	17,489,701	21,165,661	19,421,820	589,000	267,800
	Total Bid Level Cost	**192,386,714**	**232,822,274**	**213,640,020**	**6,479,000**	**2,945,800**
18	State Furnished Materials and Expenses	4,000,000	4,500,000	4,000,000	300,000	50,000
	Subtotal	**196,386,714**	**237,322,274**	**217,640,020**	**6,779,000**	**2,995,800**
19	Contingency	39,277,343	47,464,455	43,528,004	1,355,800	599,160
	Total Construction Cost	**235,664,057**	**284,786,729**	**261,168,024**	**8,134,800**	**3,594,960**
20	Land Acquisition	39,600,000	55,800,000	16,200,000	0	0
	Interchange area plus preservation	11,890,000	11,890,000			
21	Utility Relocation	25,000,000	27,250,000	2,250,000	0	0
	Total Right--of--way Cost	**76,490,000**	**94,940,000**	**18,450,000**	**0**	**0**
	Total Construction plus Right--of--way Cost	**312,154,057**	**379,726,729**	**279,618,024**	**8,134,800**	**3,594,960**

In discussions covering each model parameter shown in tables 1 and 2 with project team specialists, the variables shown in figure 1 (to be discussed shortly) were selected as focal points for assessing subjective probabilities. The specialists felt that these variables addressed issues for which there could be significant uncertainty. Other parameters in the cost models were felt to be essentially *deterministic* and did not require analysis beyond using point estimates.

A key study assumption is worth reiterating at this point. The study made no attempt to determine the feasibility of implementing AHS, at either the technical or institutional level. Instead, we have explored the costs and benefits of alternative AHS configurations, under the assumption that these configurations perform as anticipated. Thus in analyzing uncertainty related to vehicle costs for example, our emphasis was on assessing uncertainties about costs *given* the vehicle add-on equipment specifications. We did not analyze the uncertainty about whether the technical aspects of add-ons were adequate.

Vehicle electronics cost variables. The variables (and their mnemonics used in subsequent tables and graphs) chosen for uncertainty analysis were as follows:

1. Multibeam millimeter radar and vision-based sensor initial costs. While the cost of most items on table 1 were estimated using catalogue prices of similar items or actual engineering experience, these two key sensor costs were developed using a parametric cost prediction model (PRICE) where existing equivalent systems were not in production. Inputs to the PRICE model required forecasting such things as weight and technology for production subassemblies. An “initial cost multiplier” or *icm* variable was defined for PRICE estimated sensors (point estimate of 1) to quantitatively express uncertainty in these initial costs. (icm_elec)

2. Time improvement parameter (TIP) for electronics products. This is the yearly discount factor (point estimate of 20 percent or 0.20) used to model how economic competition lowers the initial cost of these products over time. (TIP_elec)

3. Brake and steering actuator initial costs. These electro-mechanical products were estimated from discussions with an owner/operator of a local automobile repair business rather than from catalogues. An “initial cost multiplier” or *icm* variable was defined for these actuators (point estimate of 1) to quantitatively express uncertainty in these initial costs. (icm_mech)

4. Time improvement parameter (TIP) for electro-mechanical products. This is the yearly discount factor (point estimate of 10 percent) used to model how economic competition lowers the initial cost of these products over time. (TIP_mech)

A 2002 vehicle procurement year and 1 million vehicle unit market were fixed for the risk analysis (although a limited sensitivity was performed assuming other procurement years). The use of cost reduction curves for calculating unit market costs was treated as a deterministic computation. (Discussions with the vehicle cost specialist indicated that reasonable changes in the choice of which cost reduction curve to use would not affect results significantly. The 100 thousand unit market implies costs approximately 7 percent greater than the 1 million unit market. Unit markets of still smaller size were considered of much less interest when taking into account the hoped for non-negligible market penetrations and the anticipated number of AHS ready vehicles required to utilize increased roadway capacity.)

Figure 1 lists processor/diagnostic costs in curly brackets to indicate that there emerged a contrary opinion from a different specialist elicited regarding the technical requirements of processing power of different AHS vehicle options relative to the ARV. Strictly speaking, since this risk analysis is confined to cost rather than technical requirement uncertainties, we used the processor assumptions described in volume 3. However, a limited sensitivity analysis was performed considering the contrary viewpoint.

Roadway cost variables. Most of the variables in table 2 were treated as deterministic based on information from standard sources or engineering experience. Analogous to vehicle costs, the specifications based directly on the nature of the specific example freeway selected (highway 101) were accepted in this risk analysis and not second-guessed as to how typical such situations might be elsewhere. (See, however, the topic of *bridge crossings* below.) However, even with this specific roadway, there were uncertainties deemed worth investigating in that it was possible to imagine potential significant cost changes if particular point estimate assumptions changed. The variables chosen for uncertainty analysis were as follows:

1. Retaining walls. The uncertainty revolved around what actual percentage of the project length (point estimate of 25 percent) would require retaining walls.

2. Sound walls. The uncertainty revolved around what actual percentage of the project length (point estimate of 30 percent) would require sound walls.

3. Drainage and creek channel improvements. These costs were computed for other options relative to Option 2. The latter had some uncertainty regarding the magnitude (point estimate of $5M) of the costs.

4. Utility relocation included in construction contract. The uncertainty revolved around what allowance (point estimate of $1.5M) per 1.6 km (1 mi) is appropriate.

5, Land acquisition right-of-way costs. The uncertainty revolved around what cost (point estimate of $25) per 0.093 square m (1 ft^2) is appropriate.

6. Land area required for interchanges. The uncertainty revolved around the size required (point estimate of 0.405 hectares (1 acre)).

7. Utility relocation. The uncertainty revolved around what allowance (point estimate of $25M) per 16 km (10 mi) is appropriate.

It turns out that none of these seven variables are relevant factors for Roadway Options 1 and 4 and thus these options are treated entirely using point estimates. (Their costs from table 2 are quite small relative to the other options shown.) Only Drainage/creek channel improvement and Land acquisition right-of-way cost uncertainties are germane for Option 5, and the risk analysis takes this into account.

The risk analysis did not address particular roadway cost items, most of which were not explicitly modeled in the Roadway Infrastructure Cost Methodology. These included:

- Inflation. As per the cost methodology assumption, no escalation or deflation was considered for roadway costs.

- Management costs. These costs were not available at the time the risk analysis was performed.

- Contingency costs were treated as a deterministic 20 percent multiplier on construction costs rather than with any probabilistic analysis (e.g., contingency costs were treated as pro forma parts of a contract protocol).

- Support building costs for roadway infrastructure were ignored.

- The requirement for queuing plazas for certain options was ignored. However, a *back-of-the-envelope* computation was elicited indicating that this cost would be approximately six million dollars.

Figure 1 lists *bridge crossing* modification costs in curly brackets. Table 2 indicates that such bridge costs (Item 3) represent a large component of construction costs. Technically speaking, however, such costs are not that uncertain for the *specific road segment* because the cost parameters for such construction averaged over a number of such crossings are well documented in cost handbooks. However, the specialist acknowledged that this particular roadway segment featured bridge crossings at a frequency of 1.5 to 2 per 1.6 km (1 mi) rather than a more typical one crossing per this distance. Because this cost item is so large in magnitude, we did a limited sensitivity analysis considering the cases where the bridge crossing costs for Options 2 and 3 were postulated to be 50 percent and 75 percent of their base case bridge costs.

Cost/Benefit Summary Indices

As shown in figure 1, five indices were selected as bottom-line summary factors.

Costs. Total *vehicle capital* (acquisition) costs and total *vehicle capital plus maintenance* costs in 1994 dollars were selected representing consumer related costs. Total roadway *capital construction plus right-of-way* costs in 1994 dollars were selected representing public related costs. (The risk analysis chose to ignore roadway electronics infrastructure capital and maintenance costs, and roadway maintenance costs as being much less significant in magnitude relative to the cost indices chosen). Probability distributions for summary cost indices were estimated using the intermediate cost variables. (No additional subjective probability assessments directly using any cost summary indices were required.)

Benefits. The focus for probability assessments was on the *capacity* (expressed in vehicles/hr/lane) that could be accommodated by the AHS1 and AHS2 vehicle options. For capacity, only the AHS1 and AHS2 distinction (i.e., manual versus automated lane changes) was considered relevant in these assessments. The focus on capacity relates especially to the following specific premise: whether or not an AHS should be built to relieve congestion in cities may hinge on whether the space savings aspect of AHS (due to higher capacity per lane) offset any cost increases that may come from more complicated construction or from installation of electronics in the vehicle or on the roadside.

The risk analysis did not formally consider other possible benefits from AHS such as energy savings, pollution reduction or improved safety. These are discussed in other volumes in this report. The safety aspect of AHS, however, was identified as a key factor affecting potential market penetration. Safety from a market penetration perspective is discussed below.

Market penetration. Subjective probability assessments of *market penetration* (defined as the percentage of registered vehicles consumers would equip for AHS2) were elicited for different market penetration scenarios. The market scenarios were defined by two parameters: acquisition cost in 1994 dollars of the vehicle electronics add-on (a $1000 and $2000 case were assessed), and the percent of freeway lane kilometers available for AHS2 operation (a 10 percent and 20 percent case were considered). A reference region for thinking about these assessments was the Los Angeles area assumed to involve a steady state future situation consisting of 10 million registered vehicles and 3600 lane kilometers of freeway. These assessments were used to develop overall distributions on market penetration considering both the uncertainty in actual vehicle acquisition costs and uncertainty in market penetration given such costs.

Finally, the potential impact of AHS safety on market penetration was considered as follows. The specialist felt that AHS as a new technology would not penetrate the market significantly unless it was shown to be safer vis-a-vis fatality accident rates than conventional alternatives. The market penetration issue was how much safer did AHS need to be for "market acceptance." Subjective probability assessments as to the fraction (less than 1) of the conventional fatality accident rate required for AHS acceptance were elicited.

In summary, section 2 described the factors that were chosen as focal points for the assessing of subjective probabilities. Uncertainty in these factors affects the uncertainty in the summary cost/benefit indices for the different vehicle and roadway modification AHS deployment scenarios.

3. PERCENTILE ESTIMATES ASSESSMENT FOR KEY FACTORS

This section describes the process by which subjective probability assessments were elicited from project team specialists. The results of this process in the form of percentile estimates were tabulated for each key factor identified in section 2. These percentile estimates are then used to develop three-point probability distribution approximations for each key factor.

Percentile estimates for each key factor were assessed from specialists using formal subjective probability assessment techniques.[2] In addition to formalizing parameter uncertainties quantitatively, these techniques help prevent common pitfalls such as understating the uncertainty in knowledge that is present about key parameters, and promote internal consistency.

The protocol used to perform these assessments for each of the factors described in section 2 consisted of the following sequence.

1. The specialist was asked to specify a level such that there was only a 5 percent probability the factor would be greater than this level (more loosely speaking, a level such that it would be surprising if the factor exceeded that level but not implausible). When asked to begin thinking of such a plausible higher level, the specialists elicited would often volunteer that the level they specified represented the 95th percentile before the assessor asked if that seemed appropriate.

2. The specialist was then asked (in a way analogous to the immediately preceding) to specify a level such that there was only a 5 percent probability the factor would be less than this level. This level represented the 5th percentile.

3. The specialist was then asked to specify a level such that the factor was just as likely to be above the level as below it. Levels between the 5th and 95th percentiles were successively suggested in a gradual “homing in” dialogue asking whether it was more likely for the factor to be above the level or below it. The process continued until the specialist felt that it would be an “even bet” that the factor would be above the final level suggested versus below that level. This level represented the 50th percentile. During this process, the specialist was reminded that it was not at all necessary for the point estimates described in the cost methodologies to be equated, say, with the 50th percentile. None of the specialists had any difficulty with this point.

4. The specialist was then asked, “given you *knew* the factor would be greater than the 50th percentile, what is the level for which it would be an even bet that the factor would be above it versus below it.” This level represented the 75th percentile.

5. The specialist was then asked, “given you *knew* the factor would be less than the 50th percentile, what is the level for which it would an even bet that the factor would be above it versus below it.” This level represented the 25th percentile.

6. The specialist was then asked if it represented a fair or even bet that the factor was between the 25th and 75th percentiles versus being outside this interval. For most of the assessments, the specialists answered yes to this question showing internal consistency. Occasionally, some slight adjusting of the 25th and 75th percentiles was performed to obtain this consistency.

7. The specialist was also asked if the 25th percentile divided the 5th to 50th percentile interval into approximately equally likely intervals. Technically, the 27.5 percentile would do this. But an affirmative answer to this question suggested that the assessed 5th percentile level was indeed reasonably close to that percentile as opposed to the known tendency for some subjects to state a less extreme percentile (like the 15th or 20th) but claim it represents the 5th percentile. The specialists responded with an affirmative confirmation to this consistency check.

8. The specialist was also asked if the 75th percentile divided the 50th to 95th percentile interval into approximately equally likely intervals. Technically, the 72.5 percentile would do this. But an affirmative answer to this question suggested that the assessed 95th percentile level was indeed reasonably close to that percentile as opposed to the known tendency for some subjects to state a less extreme percentile (like the 85th or 80th) but claim it represents the 95th percentile. The specialists responded with an affirmative confirmation to this consistency check.

The results of using this protocol for the factors described in section 2 are shown in table 3. A few comments now follow. The cost factors are as described above. For example, the electronics initial cost multiplier is just as likely to be above 1 as below 1. There is a 25 percent chance of it being below 0.85 (i.e., the actual initial 1994 dollar cost has a 25 percent chance of being less than 0.85 of the point estimate cost for the radar and vision-based sensors).

For the AHS1 capacity assessment, the specialist felt that without automated lane changing, the actual capacity realized by the system would hardly be better than a conventional system; that is, the manual lane changing problem would make it difficult to achieve capacity gains. The *Processor assessment* was elicited to reflect the specialist’s contrary opinion about how to cost out processor requirements. It represents the 1994 initial dollar cost of a processor required for the radar of an ARV. For this specialist, this represented a *unit* of processing power with which other processor/diagnostic requirements could be scaled.

Table 3. Individual factor percentile assessments.

Subjective probability assessments

Vehicle electronics cost	Percentiles				
Electronics:	5th	25th	50th	75th	95th
Initial Cost Multiplier (icm)	0.5	0.85	1	1.25	2
Time improvement parameter	0.15	0.22	0.25	0.28	0.4

Notes: Electronics icm applies only to radar and vision-based sensors

Electro-mechanical:	5th	25th	50th	75th	95th
Initial Cost Multiplier (icm)	0.4	0.68	1	1.56	2.5
Time improvement parameter	0.05	0.09	0.12	0.14	0.2

Notes: Electro-mechanical icm applies only to brake actuator and steering actuator

Roadway costs	5th	25th	50th	75th	95th	Notes
Retaining Walls (02)	15%	24%	30%	38%	60%	% project length
Soundwalls (05)	20%	26%	33%	40%	50%	% project length
Drainage & Creek (09)	3	5.5	7	9	12	ratios to $5M
Utility Reloc incl (15)	0.8	1.2	1.5	1.8	2.5	$M/mi allowance
Land Acquisition (20)	15	24	30	34	50	$/sq. ft
Land Acquisition (20)	0.6	0.9	1	1.3	2	acres/interchange
Utility Relocation (21)	10	20	25	28	35	$M/10 mi allowance

Additional factors	5th	25th	50th	75th	95th	Notes
Capacity (AHS1)	1800		2200		2600	vehicles/lane/hr
Capacity (AHS2)	4500	5300	5800	6300	7500	vehicles/lane/hr
% registered veh - $1K/vehicle	15%	25%	35%	40%	50%	Market penetration
% registered veh - $2K/vehicle	5%	9%	12%	15%	20%	Market penetration
Processor "unit" base$	500		1500		3000	
Fatal accident rate	0.5				0.05	AHS/conventional

Notes: Market penetration assumes 20% of freeway lane miles are AHS.
A criticial mass for penetration is 10% of freeway lane miles.

Vehicle cost add-on:	$500	$1,000	$1,500	$2,000	$3,000	
median % registered vehicles	50%	20%	10%	5%	2%	AHS freeway - 10%
median % registered vehicles		35%		12%		AHS freeway - 20%

The *Fatality accident rate* improvement requirement assessment indicated that there is only a 5 percent chance of market acceptance (i.e., non-rejection) on the safety issue if an AHS has only 0.5 (one-half) the fatality accident rate of the conventional alternative. There is a 95 percent chance of acceptance on the safety issue if the AHS fatality accident rate is 0.05 (one-twentieth) the conventional alternative.

Finally, the last few lines of the table outline a functional relationship between market penetration and the two parameters of vehicle electronics acquisition cost and percentage of available AHS freeway lane kilometers. For example, given 10 percent of the freeway lane kilometers are available for AHS, market penetrations are 20 percent of the registered vehicles for a $1,000 add-on cost and 5 percent for a $2,000 add-on.

Given the percentile estimates shown in table 3, we used the three-point Pearson-Tukey discrete probability distribution to approximate the uncertainty in each factor for purposes of calculating the *mean* and *variance* of individual factors and functions of these factors.[3,4] The Pearson-Tukey or PT three-point approximation replaces the actual probability density function of any continuous factor as defined above with the following three-point discrete probability distribution:

probability (x) = 0.185	if x = 5th percentile.
probability (x) = 0.63	if x = 50th percentile.
probability (x) = 0.185	if x = 95th percentile.
probability (x) = 0	otherwise.

This three-point PT approximation has been shown to give excellent results in estimating the mean and variance for a wide variety of probability distributions for uncertain factors and functions of those factors.[3,4] This approximation is also superior to other suggested *universal* three-point approximations in this regard, and even suggested five point approximations. (It is also superior to simulating in most cases unless the number of simulations becomes enormous. It also gives reproducible results not dependent on a simulation random starting seed.)

As will be elaborated on in sections 4 and 5, the assessed percentile points were used subsequently as follows:

- all percentiles are used in a sensitivity analysis diagram (called a tornado diagram) to show how the cost methodology point estimate summary indices would change as each single factor is varied from its 5th through its 95th percentile level. The percentiles are also interesting in their own right for insight about what uncertainty is present in the current state of knowledge for each factor.

- the PT approximations are used to estimate the mean and variance of summary indices and to derive probability distributions on the summary indices. Although the 25th and 75th percentiles are not part of the PT approximation, they were still useful indirectly by: a) helping to provide an approximate consistency check that the 5th and 95th percentiles were reasonably assessed as described in the protocol above, and b) helping to provide an approximate consistency check on the summary indices distributions derivation by means of an alternate calculation (described in the appendix).

In summary, the main results of section 3 are the subjectively assessed percentile estimates for each key factor as shown in table 3. The protocol for obtaining these assessments allowed project specialists for vehicle costs, roadway modification costs, and capacity/market penetration respectively to systematically quantify their judgmental uncertainty about these factors. The percentile estimates were then used to develop approximate three-point discrete probability distributions for each factor. These three-point distributions provide the mechanism for ultimately deriving the probability distributions on the cost/benefit summary indices

4. DEVELOPMENT OF A SIMPLIFIED FRAMEWORK DELINEATING RELATIONSHIPS AMONG INTERMEDIATE AND SUMMARY COST/BENEFIT FACTORS

This section describes how the three-point approximations developed in section 3 are used to develop probability distributions for the cost/benefit summary indices. Formulas were developed relating intermediate and summary cost/benefit facts. Most of the relationships concern those between the various cost parameters that go into computing overall vehicle electronics add-on and roadway capital/construction cost summary indices. These will be described first followed by relationships involving market penetration estimation. Also discussed are formulas relating the means and variances of individual factors to those of the summary indices, and formulas for the probability distribution derivation for the summary indices.

Vehicle Capital Costs (Electronics Add-On)

Table 1 shows the summary point estimate computation for the electronics add-on package to a vehicle for the different vehicle options. As described in volume 3, each cost component was arrived at by estimating an initial cost and then applying time improvement factors and unit production cost reduction factors to arrive at the result such as that shown in table 1. At the bottom of the first page of table 1 are the summation of the individual capital cost components separated into four groupings (labeled v1 through v4).

The risk analysis developed a formula to take as input the summary four grouping figures in table 1, infer original initial cost estimates, and then recompute a summary figure based on alternative estimates for the four factors involving uncertainty described in section 2 for vehicle electronics cost. The formula developed is:

Vehicle capital costs =

$$(v2*icm\_elec+v3)*e\_init*(1-TIP\_elec)^{n}+ (v1*icm\_mech+v4)*m\_init*(1-TIP\_mech)^{n} \quad (1)$$

where:

- v1, v2, v3, v4 are the four groupings at the bottom of table 1 for vehicle procurement;
- icm_elec, TIP_elec, icm_mech, TIP_mech are the four factors regarding vehicle costs for which percentiles were assessed in table 3;
- n equals the number of years over which the time improvement parameter or TIP operates (e.g., n=8);
- e_init = $1/(1-0.2)^{n}$ (= 5.96 for n=8) is the factor for computing the initial cost before any TIP_elec was considered;
- m_init = $1/(1-0.1)^{n}$ (= 2.323 for n=8) is the factor for computing the initial cost before any TIP_mech was considered.

When initial point estimates for the uncertain factors are inserted in this formula, the results shown in table 1 are obtained. (The formula is based on a purely empirical relationship that was noticed in which adding the term of 0.06 to the two original TIPs in a discounting-like formula seemed to reproduce reasonably well the calculations of support costs available at the time of this risk analysis.) This formula allows alternate estimates (selected assessed percentile points, for example) to be used instead of the original point estimates to help compute risk analysis results (e.g., means variances, tornado diagram points) as shown in section 5.

Vehicle Capital and Maintenance Costs (Electronics Add-On)

The second page of table 1 shows the summary vehicle seven year support (maintenance) costs. At the bottom of the second page of table 1 are the summation of the maintenance individual cost components separated into two groupings (labeled vm1 and vm2).

The risk analysis developed a simplified formula to take as input the summary two grouping maintenance figures in table 1, and then recompute a summary figure based on alternative estimates for the two TIP parameters involving uncertainty described in section 2 for vehicle electronics cost. The formula developed is:

Vehicle maintenance costs =
$vm1*ma\_e\_init*(1-TIP\_elec-0.06)^n+$
$vm2*ma\_m\_init*(1-TIP\_mech-0.06)^n$

where:
$ma\_e\_init = 1/(1-0.26)^n$ (= 11.12 for n=8) is the factor for computing the electronics maintenance cost before any TIP_elec was considered
$ma\_m\_init = 1/(1-0.16)^n$ (= 4.034 for n=8) is the factor for computing the electro-mechanical maintenance cost before any TIP_mech was considered

When initial point estimates for the uncertain factors are inserted in this formula, the results shown in table 1 are obtained. (The formula is based on a purely empirical relationship that was noticed in which adding the term of 0.06 to the two original TIPs in a discounting-like formula seemed to reproduce reasonably well the calculations of support costs available at the time of this risk analysis.) This formula allows alternate estimates (selected assessed percentile points, for example) to be used instead of the original point estimates to help compute risk analysis results (e.g., means variances, tornado diagram points) in Step 4. This formula allows alternate estimates (selected assessed percentile points, for example) to be used instead of the original point estimates to help compute risk analysis results (e.g., means variances, tornado diagram points) in section 5.

In implementing the maintenance formula to obtain capital and maintenance costs, the maintenance term related to electronics costs was simply added to the electronics cost term of formula (1) while the electro-mechanical maintenance cost term was added to the electro-mechanical cost term. The reason for separating the capital and maintenance *electronics* and *electro-mechanical* costs into two distinct terms to be summed is related to mean and variance computations discussed below.

Roadway Capital Costs (Total Construction Plus Right-of-Way)

The formulas for deriving these costs are all documented in volume 4 of this report. The formulas include how the factors identified for uncertainty analysis are used to compute the cost *items* 2, 5, 9, 15, 20 and 21 shown in table 2. These formulas were implemented so that the cost items in table 2 could be recomputed depending on factor level assignments.

The bottom-line cost figure (total construction plus right-of-way cost) in table 2 can be viewed as coming from summing: items 1 through 16 each multiplied by the factor 1.32 (1.1*1.2 to include mobilization and contingency), item 18 multiplied by 1.2, and items 20 and 21. Item 20 or land acquisition is a combination of purchasing right-of-way along the route and land for interchanges. Both the amount of interchange land and its price affect the cost of the interchange property purchased.

Capacity

The percentiles for this index were directly assessed (see table 3) for AHS1 and AHS2 and required no further computation or analysis. Comments on the uncertainty about AHS2 capacity in relation to the uncertainty about AHS vehicle add-on costs are presented in section 5.

Market Penetration

The risk analysis developed simplified formulas relating the mean and standard deviation of market penetration to vehicle capital costs and percentage of available AHS freeway kilometers. The mean market penetration (for capital costs greater than $500) equals:

$$\max((34\% - 73\% * \log_{10}(\text{capital cost in \$K})), 0) \text{ for 20\% AHS availability} \quad (2)$$

$$\max((12\% - 50\% * \log_{10}(\text{capital cost in \$K})), 0) \text{ for 10\% AHS availability} \quad (3)$$

The market penetration was assumed to be normally distributed about the mean, with a standard deviation equal to 0.33*mean for each case. (See section 5 below for how particular coefficients/fits were estimated from the assessed data.)

These formulas were derived by postulating a simple linear relationship between the log of capital costs and mean market penetration, and then solving the linear relationship exactly using the estimated means for the 20 percent AHS availability and point estimates for the 10 percent AHS availability based on assessments in table 3 for the $1,000 and $2,000 capital cost cases respectively. Although coarse, the formulas do give plausible numbers and seemed suitable for the very approximate analysis for which they were employed in section 5.

Mean and Variance Calculations

Means and variances of factors and functions of factors were estimated using the PT three-point approximations as follows:

Individual factors:

$$\text{mean} = 0.185*(\text{5th percentile} + \text{95th percentile}) + 0.63*(\text{50th percentile}) \quad (4)$$

$$\text{variance} = 0.185*((\text{5th percentile})^2 + (\text{95th percentile})^2) + 0.63*(\text{50th percentile})^2 - \text{mean}^2 \quad (5)$$

(The standard deviation or std is equal to the square root of the variance.) Note that the variance equals the mean of the square minus the square of the mean (e.g., see reference 5 for statistical formulas).

All the factors for which percentiles were assessed in table 3 are assumed to be mutually *probabilistically independent* (heuristically, being told the level of one variable does not change the uncertainty distributions for the other variables).

Cost elements which are functions of a unique single factor:

The mean and variance of such a cost element is obtained by using the *cost* corresponding to (i.e., computed using) each factor percentile, in place of those percentiles in formulas (4) and (5). The cost elements having this property are roadway cost items 2, 5, 9, 15, and 21 in table 2.

Elements which are functions of two independent factors:

For vehicle costs, the electronics cost is a function of icm_elec and TIP_elec, while the electro-mechanical cost is a function of icm_mech and TIP_mech. For roadway costs, total land acquisition costs (item 20 in table 2) is a function of the acquisition price and the interchange area required. For these cases, the PT approximation is first used to derive the probabilities for each possible combination of factor levels. The mean and mean of the square (and from them the variance) of the cost element is then computed using the cost corresponding to each percentile combination and the following combination *weights*:

	Factor A:	5th	50th	95th
Factor B	5th	0.185*0.185	0.185*0.63	0.185*0.185
	50th	0.63*0.185	0.63*0.63	0.63*0.185
	95th	0.185*0.185	0.185*0.63	0.185*0.185

The nine combination probabilities come directly from the assumption that the factors are probabilistically independent (e.g., *given* the 5th percentile on Factor B, the same probability distribution is expected for the 5th, 50th and 95th percentiles on Factor A as originally assessed).

Summary cost indices which are sums of independent random variables:

Once the means and variances of the cost elements described above have been computed, for our case where these cost elements are probabilistically independent of each other we can compute:

overall mean = sum of the means
overall variance = sum of the variances

Thus for the vehicle costs, the mean is the sum of the means of the electronic and electro-mechanical costs (assumed to be independent of each other) and the variance is the sum of their respective variances. For roadway costs, the computed means for items 2, 5, 9, 15, 20 (in total) and 21 are substituted into the sum in table 2 to compute an overall mean. The overall variance is equal to: 1.32*1.32 *(sum of the variances of items 2, 5, 9 and 15) + (sum of the variances of item 20 (in total) and item 21). We need to multiply the variance of the indicated items by 1.32 squared because the variance of a constant times a variable is the constant squared times the variance of the variable. This properly takes into account the effect of the mobilization and contingency multipliers on the variance of the roadway costs.

<u>Market penetration</u>:

This represents a case where *conditional* on a vehicle cost, we get a distribution on the market penetration percentage and we must then *integrate* this over possible vehicle capital costs to arrive at an overall mean and variance for market penetration. Computationally, this case turns out to be very similar to the two-factor combination *matrix*. We first develop a separate PT three-point approximation for the summary vehicle capital cost. Now, however, the market penetration percentiles are not independent of the capital cost percentiles. But, we have a relationship giving the market *mean* conditional on any given vehicle capital cost, namely formulas (2) and (3). For a given cost, the market penetration 5th, 50th and 95th percentiles are (*mean* - 1.645* std), *mean* and (*mean* + 1.645* std) when a normal distribution is assumed. Using this relationship, we compute a total of nine market penetrations (three each for the 5th, 50th and 95th vehicle capital cost percentiles) and compute the mean and mean of the square with the matrix weights shown previously.

Deriving an Overall Distribution on a Summary Index Given Its Mean and Variance

Finally, after computing the mean and variance of a summary index using the PT approximations, we fit these parameters to an overall distribution. In this analysis, we have chosen a lognormal distribution (so-called because the log of the variable is distributed normally) for this fit. (See reference 5 for details of the lognormal distribution). This distribution is reasonable for the summary indices for the following reasons:

- it is the distribution having the maximum entropy (least assumed "information content") when all that is known about a variable is its mean, variance, and that it is nonnegative.[6]
- for a *coefficient of variation* or COV (the ratio of a variable's standard deviation to its mean) that is small (e.g., less than 0.2), the lognormal and normal distributions are very similar and so for sums of variables having this property, one does not really lose the advantage of sums of variables sometimes being well approximated by a normal distribution if one uses a lognormal instead.
- for a coefficient of variation that is somewhat larger, the lognormal captures the property that is often present of there being a distinct skew to the right, which is not well modeled using a normal distribution.

The algorithm for fitting a lognormal proceeds as follows:[5]

1. the *sigma* parameter = sqrt(ln(1+COV^2)), where sqrt means square root.
2. the *mu* parameter = ln(mean) - 0.5*$sigma^2$, where ln means natural log.

To compute any percentile of the lognormal, one uses the percentile points of the "underlying" normal distribution and exponentiates them. For example,

5th percentile = exp(mu - 1.645*sigma), where exp(x) mean e^x

50th percentile = exp(mu)

95th percentile = exp(mu + 1.645*sigma)

The lognormal fit was felt to be the best way to estimate the so-called credibility interval (5th to 95th percentile range) of the summary indices, because it is a commonly-used flexible distribution and it is based on the mean and variance which can be computed somewhat robustly using the PT three-point approximations. However, as a partial check on the credibility interval computations for the summary indices, we made use of other approximations, which are not as good as the PT, but could at least provide a check. These check calculations, described in the appendix, gave 5th, 50th and 95th percentile results very similar to that of the lognormal.

The lognormal distribution has the property that the ratio of the 95th to the 50th percentile is equal to the ratio of the 50th to the 5th percentile. This ratio is equal to exp(1.645*sigma). For example, if sigma were equal to 0.67, the preceding ratio is equal to approximately 3. In relative terms, the credibility interval is sometimes characterized in terms of this ratio (e.g., a "factor of 3" about the median).

In summary, the main result of section 4 is the development of a quantitative framework for relating the factors about which uncertainties have been assessed to the summary cost/benefit indices of interest. This framework contain formulas that calculate how the summary indices change in response to changes in the input factors. Using these formulas, the framework derives lognormal probability distributions on the summary cost/benefit indices based on the subjectively assessed percentiles of the input factors. The lognormal distributions allow for the calculation of uncertainty ranges (credibility intervals) in the summary indices as a indication of the *risk* due to uncertain knowledge.

5. FRAMEWORK IMPLEMENTATION AND RISK ANALYSIS RESULTS

This section describes the results of implementing the framework described in section 4 for different AHS scenarios. The first results presented are sensitivity analyses showing how each cost summary index point estimate changes in response to changes of individual factor inputs across their credibility ranges. These sensitivity analyses provide insight as to which factors have the most effect on the uncertainty in the cost summary indices. Then the derived overall distributions for the cost summary indices, as well as capacity and market penetration are presented and discussed along with their credibility intervals. These overall distributions represent the key results of the risk computations. Finally, selected additional sensitivity analyses are presented with regard to market penetration. The simplified framework from section 4 was implemented using EXCEL spreadsheet software. Graphs and tables of sensitivity analysis and risk analysis distribution outputs were generated to highlight the likelihood of various costs/benefit levels ensuing from different AHS alternatives. Presented below are the main results of the risk analysis computations.

Tornado Diagrams for Summary Cost Indices

The first kind of risk analysis result explores how the summary point estimate costs would change when each factor is set at its 5th, 25th, 50th, 75th and 95th percentile (or *fractile*) respectively while all the other factors remain at their originally assigned point estimates. When such cost variations are sorted by the cost spread from 5th to 95th percentile and then plotted from top to bottom, a type of "tornado" diagram (see for example, references 4 and 7) is produced. The tornado diagrams described here indicate the relative sensitivity of summary cost indices for each AHS option to variations of each factor individually over its *credibility* interval. Figure 2 shows tornado diagrams for the seven vehicle options, while figure 3 shows tornado diagrams for the three roadway retrofit options that were not considered deterministic.

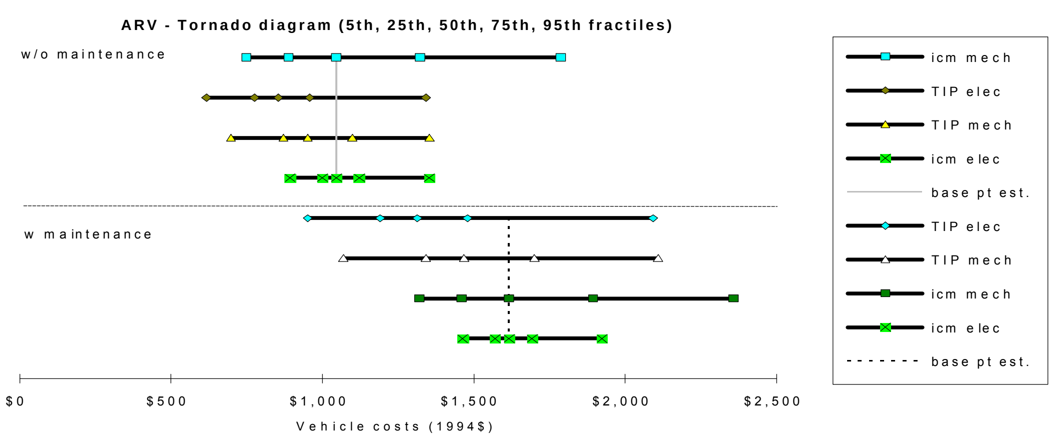
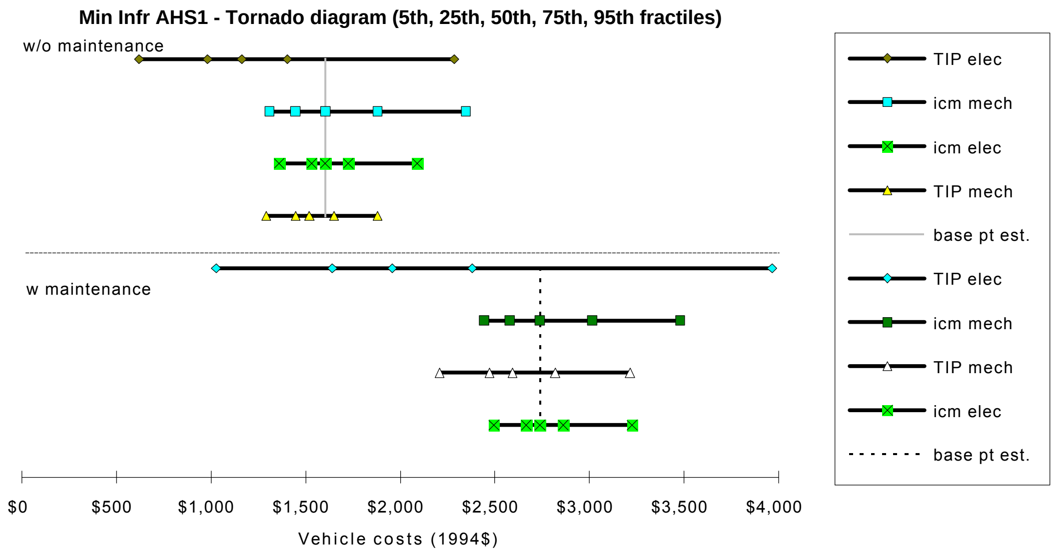


Figure 2. Vehicle cost tornado diagrams.



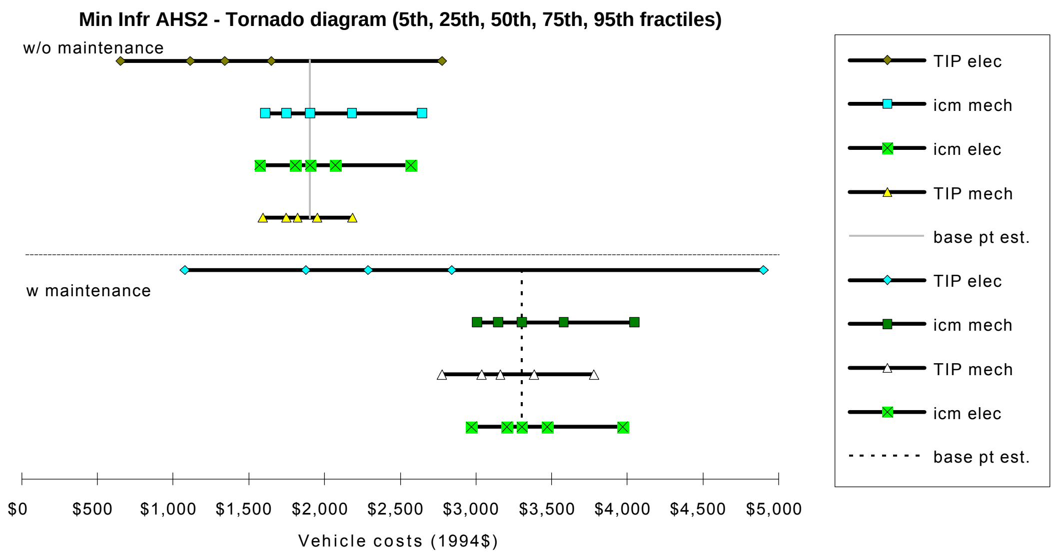
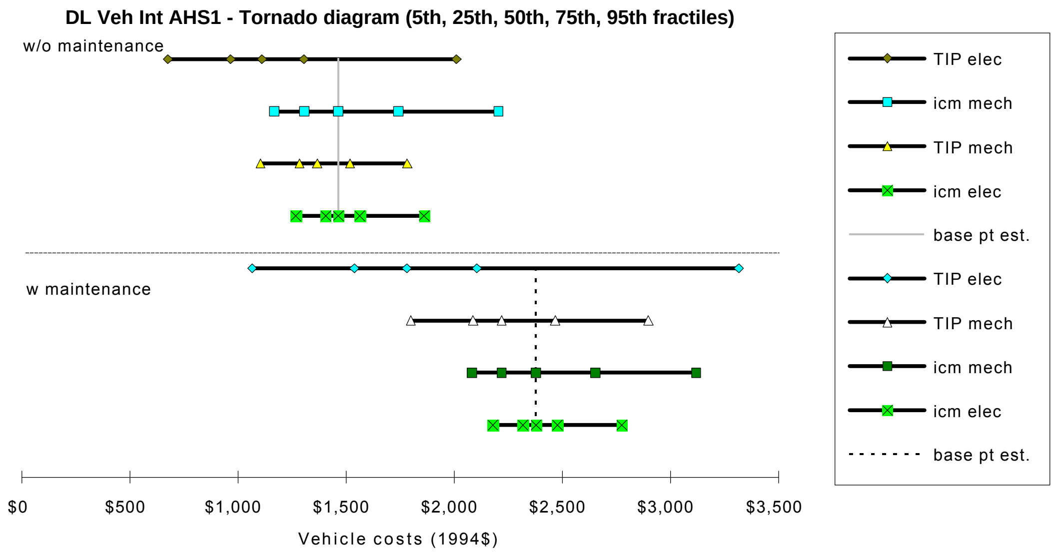


Figure 2 (continued). Vehicle cost tornado diagrams.



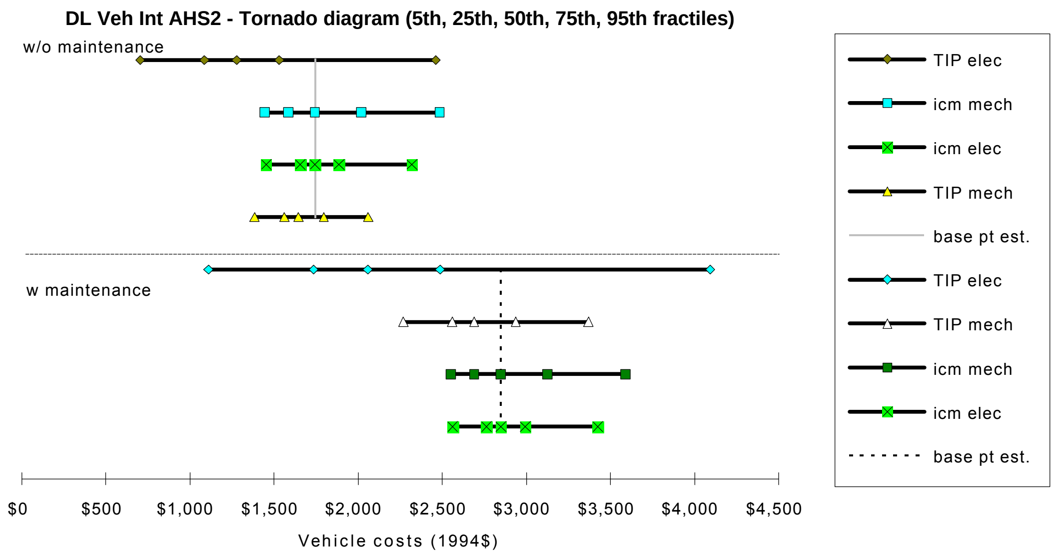
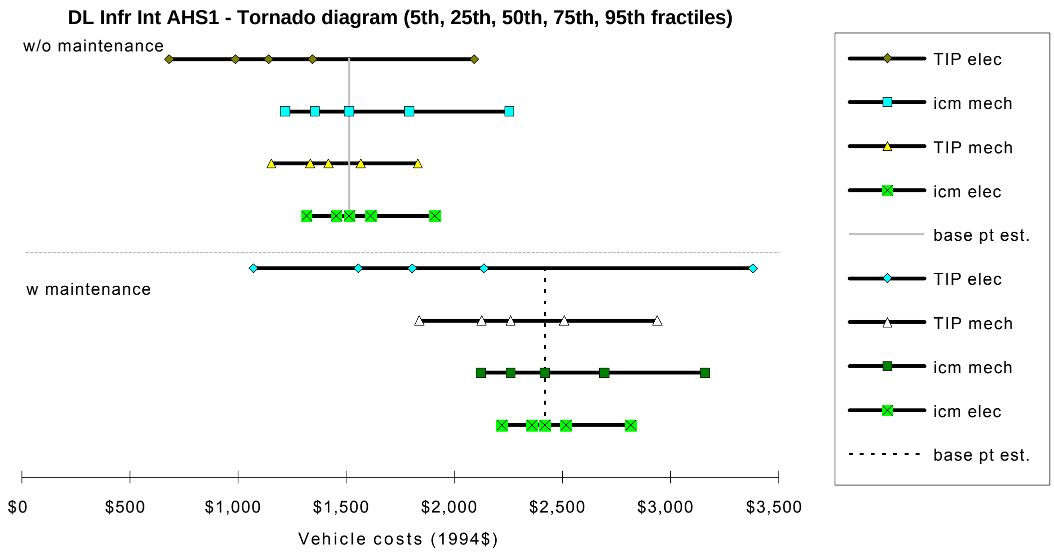


Figure 2 (continued). Vehicle cost tornado diagrams.



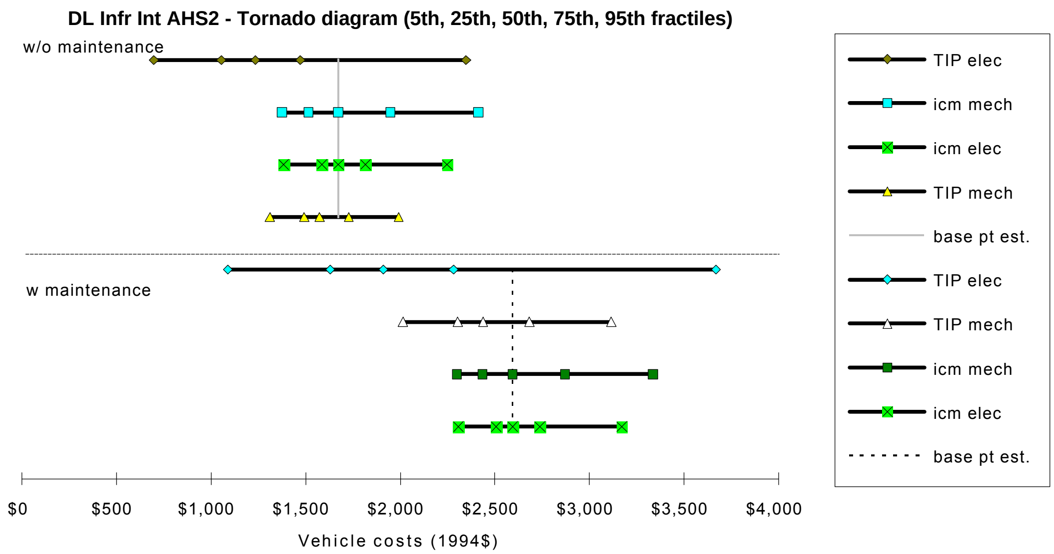
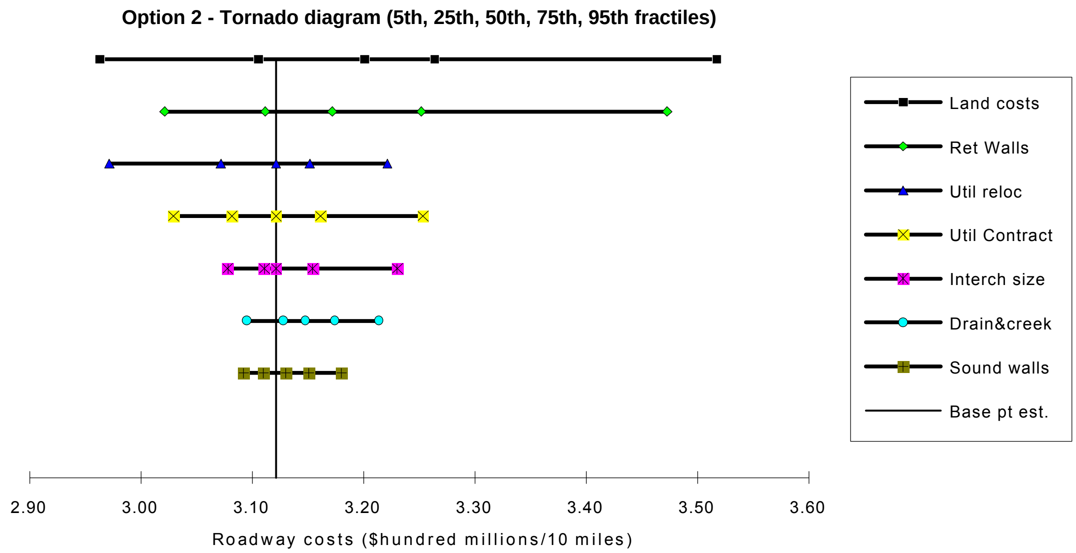


Figure 2 (continued). Vehicle cost tornado diagrams.



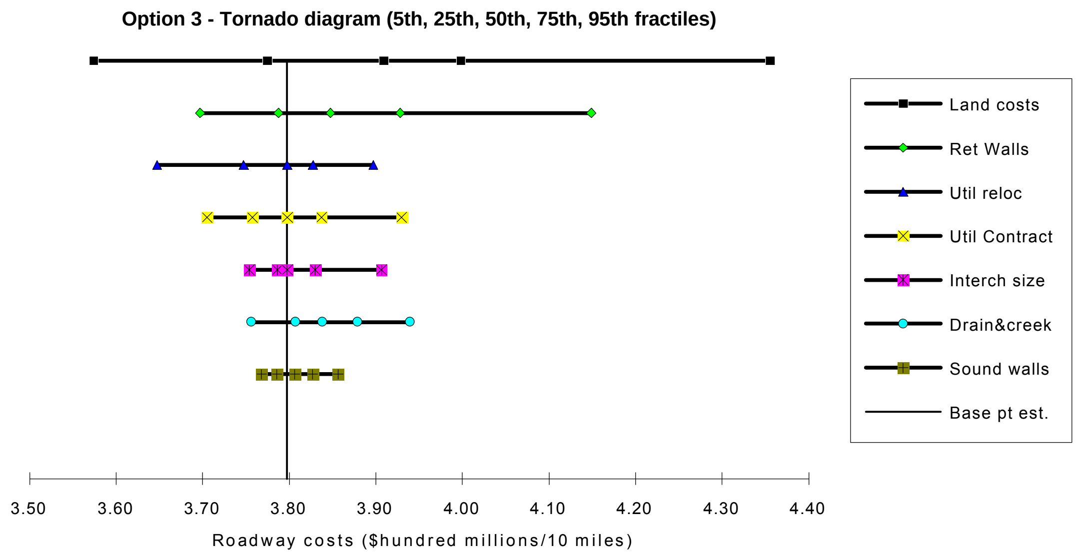


Figure 3. Roadway cost tornado diagrams.

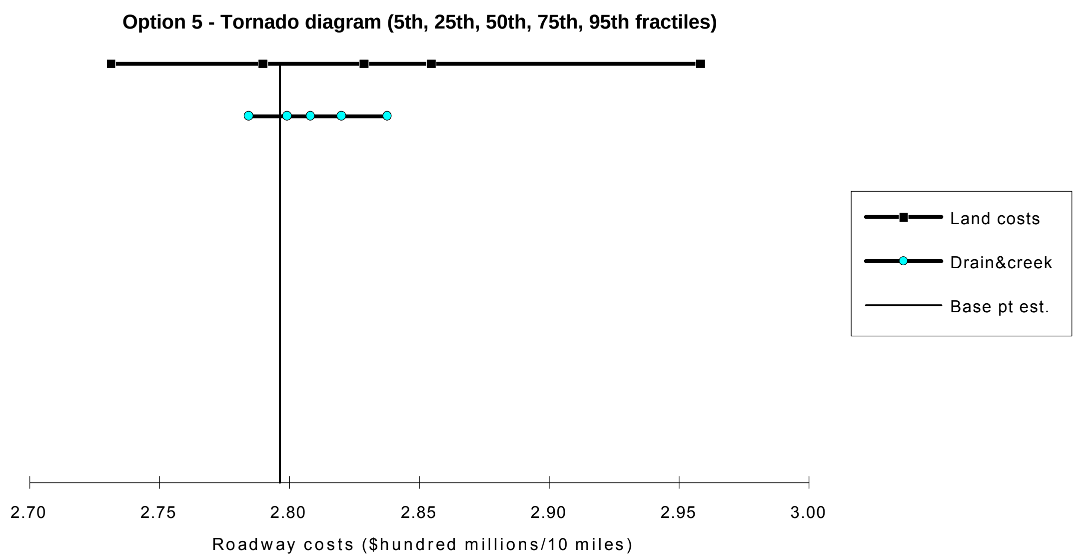


Figure 3 (continued). Roadway cost tornado diagrams.

The vehicle cost spreads in figure 2 come about from a combination of both the degree of uncertainty in each factor listed and the importance of that factor to vehicle costs. The TIP_elec parameter appears at the top of the tornado diagrams for all cases shown except the ARV procurement costs. As can be seen from the cost summary groupings at the bottom of table 1, for the ARV case, the actuator components represent a larger fraction of the procurement costs than in the case of more advanced vehicle alternatives where non-electro-mechanical components represent a much larger fraction. The level assigned to the TIP_elec parameter can have a significant effect on vehicle cost estimates. This factor is relatively critical in estimating if truly dramatic electronics cost reductions over time can occur due to economic competition. The TIP_elec *point estimate* of 20 percent was such that the tornado diagrams show significant possibilities of lower costs (relative to the base point estimate) as this parameter is varied.

The roadway costs results in figure 3 come about from a combination of both the degree of uncertainty in each factor listed and the importance of that factor to roadway retrofit costs. Land costs appear at the top of the tornado diagrams shown for all cases. The point estimates for several factors were such that significant possibilities of higher costs (relative to the base point estimates) are indicated in the tornado diagrams as these factors are varied.

Overall Distributions on Summary Cost Indices

Tables 4 and 5 show features of the derived distributions on the summary cost indices. As indicated in the relationships developed in section 4, these are the lognormal distributions that aggregate the uncertainties on *all* the relevant intermediate cost parameters into a probability distribution for each summary cost index. Figures 4 and 5 show selected key features in graphical terms. Vehicle and roadway results are discussed separately below.

Vehicle costs. Table 4 shows that for vehicle costs, the initial point estimates are larger than the estimated means. This is because the TIP parameters used in the point estimates were relatively conservative when compared to the probability assessments. (The point estimates were both near the 25th percentiles of the factor assessments, and the higher the TIP factors are, the lower the cost.) The standard deviations (or std) are considerable, typically about 50 percent of the means in table 4, for example.

The 5th, 50th and 95th percentiles on vehicle costs are shown given the lognormal parameter fit (mu and sigma) to the estimated mean and standard deviation as described in section 4. They are graphed along with the mean in figure 4 and span the so-called *credibility intervals* for vehicle costs. As explained in section 4, the lognormal can be used to compute any percentile of the overall vehicle cost distribution desired. The credibility intervals are relatively large. In relative terms as described in section 4, the credibility intervals for vehicle costs are approximately a "factor of 2.2" about the median.

Roadway retrofit costs. Table 5 shows that for roadway costs, the point estimates are smaller than the estimated means. This is because particular factor point estimates were relatively *optimistic* when compared to the probability assessments. (The point estimate for land costs for example, was below the 25th percentile of the factor assessment, and the higher the price of land, the higher the overall cost.) The standard deviations (or std) are less than 10 percent of the means in table 5. The main contribution to the *variance* term comes from the land cost uncertainties and amounts to 62 percent, 72 percent and 95 percent for Options 2, 3 and 5 respectively. Retaining wall uncertainties provide 23 percent and 16 percent of the variance for Options 2 and 3 respectively.

The 5th, 50th and 95th percentiles on roadway costs are shown given the lognormal parameter fit (mu and sigma) to the estimated mean and standard deviation as described in section 4. They are graphed along with the mean in figure 5 and span the so-called *credibility interval* for roadway costs. The relative symmetry of the credibility intervals around the median (especially when compared to vehicle costs) reflect a relatively small coefficient of variation (std less than 10 percent of the mean).

Table 4. Probability distributions on summary vehicle costs.

Vehicle costs (excluding maintenance)

				Dedicated Lanes			
		Mixed Traffic		Vehicle Intensive		Infrastructure Intensive	
	ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
Point estimate	$1,045	$1,604	$1,905	$1,464	$1,742	$1,514	$1,672
Grand mean	$926	$1,315	$1,536	$1,227	$1,431	$1,261	$1,383
Grand variance	2.28E+05	4.82E+05	7.05E+05	3.75E+05	5.47E+05	3.97E+05	5.09E+05
Grand std	$478	$694	$840	$612	$740	$630	$714
Lognormal distribution fit							
5th percentile	$370	$515	$581	$505	$571	$519	$552
50th percentile	$823	$1,163	$1,348	$1,097	$1,272	$1,129	$1,229
95th percentile	$1,830	$2,629	$3,125	$2,384	$2,831	$2,452	$2,733
mu	6.713	7.059	7.206	7.001	7.148	7.029	7.114
sigma	0.486	0.496	0.511	0.472	0.486	0.472	0.486

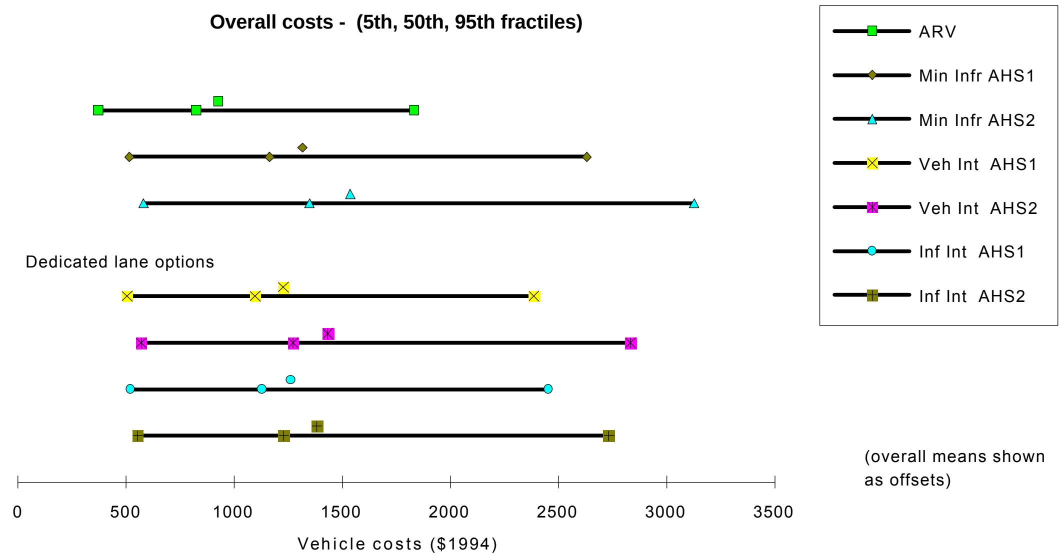
Vehicle costs (including maintenance)

				Dedicated Lanes			
		Mixed Traffic		Vehicle Intensive		Infrastructure Intensive	
	ARV	AHS1	AHS2	AHS1	AHS2	AHS1	AHS2
Point estimate	$1,616	$2,738	$3,304	$2,377	$2,848	$2,418	$2,594
Grand mean	$1,379	$2,160	$2,563	$1,920	$2,258	$1,949	$2,083
Grand variance	3.79E+05	1.16E+06	1.83E+06	7.94E+05	1.23E+06	8.22E+05	9.98E+05
Grand std	$615	$1,078	$1,351	$891	$1,109	$907	$999
Lognormal distribution fit							
5th percentile	$624	$890	$1,004	$842	$943	$853	$888
50th percentile	$1,259	$1,933	$2,267	$1,742	$2,026	$1,767	$1,878
95th percentile	$2,538	$4,198	$5,121	$3,602	$4,354	$3,660	$3,970
mu	7.138	7.567	7.726	7.463	7.614	7.477	7.538
sigma	0.426	0.471	0.495	0.442	0.465	0.443	0.455

Table 5. Probability distribution on summary roadway costs.

Total Construction plus Right--of--way Cost

	Option 2	Option 3	Option 5	Option 1	Option 4
Point estimate	**312,154,057**	**379,726,729**	**279,618,024**	**8,134,800**	**3,594,960**
Grand mean	**337,205,209**	**410,174,749**	**284,755,314**	**8,134,800**	**3,594,960**
Grand variance	8.61E+14	1.23E+15	5.09E+13	not applic.	not applic.
Grand std	**29,341,525**	**35,139,038**	**7,131,361**		
Lognormal distribution fit					
5th percentile	291,212,218	355,050,514	273,178,695		
50th percentile	335,935,853	408,677,830	284,666,058		
95th percentile	387,528,031	470,405,090	296,636,473		
mu	19.632	19.828	19.467		
sigma	0.087	0.086	0.025		



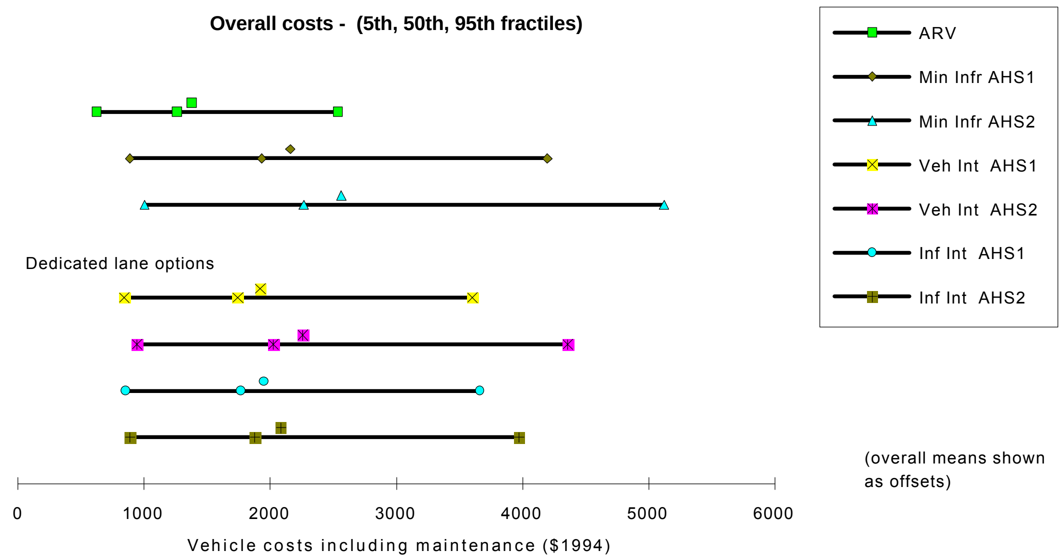


Figure 4. Vehicle cost credibility intervals.

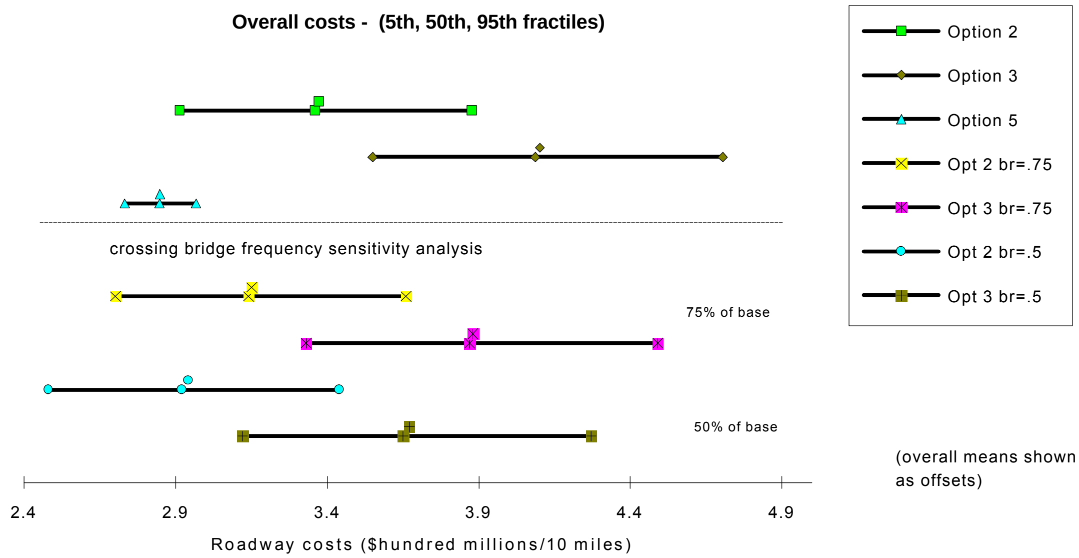


Figure 5. Roadway retrofit cost credibility intervals and bridge crossing sensitivity analysis.

Figure 5 also shows the sensitivity analysis done for different assumptions regarding the number of bridge crossings that may be more typical for a retrofit. The base case clearly shows Option 5 to be cheaper than Option 2, even when the *quite optimistic* 5th percentile costs are compared for all options. With only 75 percent of the base case bridge crossings assumed, Option 2 could be competitive with Option 5 if quite optimistic outcomes (the 5th percentile cost estimate) occurred for both options. However, with 50 percent of the base case bridge crossing assumed, the means of Options 2 and 5 are close. With optimistic outcomes (the 5th percentile cost estimates), Option 2 is cheaper while for pessimistic outcomes (the 95th percentile cost estimates), Option 5 is cheaper. Thus in this last case, it is no longer clear whether Option 2 or 5 would be the best, and land costs would clearly strongly influence the relative attractiveness of Option 2 versus Option 5.

Overall Distribution on Capacity

Using the percentiles directly assessed for the capacity (vehicles/hr/lane) resulting from an AHS2 deployment as shown in table 3, we computed a mean and standard deviation and also fit a lognormal distribution. The percentile inputs and rounded results are summarized in table 6.

Table 6. Probability distribution on capacity.

	5th	25th	50th	75th	95th
Capacity (AHS2)	4500	5300	5800	6300	7500
Capacity: Lognormal fit	4500	5200	5800	6400	7500

Lognormal parameters	Mean	Std	mu	sigma
Capacity (AHS2)	5874.00	917.51	8.67	0.16

One of the properties of the lognormal distribution is that the ratio of two independent lognormally distributed variables is also distributed lognormally with parameters:

mu = mu of the numerator - mu of the denominator and

sigma = sqrt (sigma^2 of the numerator + sigma^2 of the denominator).

If we consider the ratio of vehicle costs (see table 4) to capacity, we notice that the sigma parameters for AHS2 vehicles are close to 0.5. Substituting 0.5 and 0.16 for the numerator and denominator sigmas into the formula immediately above, we find that the sigma parameter for the ratio is about 0.525 or essentially the same as would have been the case if we ignored uncertainty in capacity altogether. Given these assessments, if a cost/benefit focus is on vehicle costs per capacity, the vehicle cost uncertainty *dominates* the uncertainty about capacity. (This result would also be obtained if the original capacity percentile assessments were expressed in terms of AHS capacity gains versus conventional capacity; e.g., if conventional capacity were fixed at 2000, such percentiles would be 2.25, 2.65, 2.9, 3.15 and 3.75).

Overall Distribution on Market Penetration

Table 7 recaps market penetration percentile assessment input, and relational assumptions described in section 4 above. The specialist's judgments involved comparing the perceived consumer value of the benefits obtained from the vehicle cost add-on in view of other historical add-ons and their market penetrations (e.g., ABS brakes).

The market penetration fractile inputs are not too asymmetrical about the estimated means. The ratio of the standard deviation to the mean was also similar in both the $1,000 and $2,000 add-on cases (0.31 and 0.37 respectively). Given these observations, the assumption of a market penetration normally distributed about its mean with a standard deviation equal to 0.333 of its mean was made.

Table 7. Market penetration modeling data and calibration.

Overall distribution on market penetration (MP in % of registered vehicles) calculations
Subjective percentile assessments recap: (COV = ratio of std to the mean)

	percentiles							
MP given vehic add-on cost	5th	25th	50th	75th	95th	mean	std	COV
% registered veh - $1K/vehicl	15%	25%	35%	40%	50%	34%	11%	0.31
% registered veh - $2K/vehicl	5%	9%	12%	15%	20%	12%	5%	0.37

Notes: Market penetration assumes 20% of freeway lane miles are AHS.
A criticial mass for penetration is 10% of freeway lane miles.

Vehicle cost add-on:	$500	$1,000	$1,500	$2,000	$3,000	
median % registered vehicles	50%	20%	10%	5%	2%	AHS freeway - 10%
median % registered vehicles		35%		12%		AHS freeway - 20%

Assumptions based on assessments above:
MP is distributed normally with std = 0.333* mean (COV assumed equal to 0.333)

	a	b	AHS freeway
log (mean MP) = a+ b* log (vehicle add-on cost in $K)			
(a, b parameters based on vehicle cost $1K & $2K assessments)	20%	-50%	10% lane miles
	34%	-73%	20% lane miles

Model fit illustration: Vehicle add-on cost in thousands of dollars

	0.50	1.00	1.50	2.00	3.00	4.00	AHS freeway
Mean MP =	35%	20%	11%	5%	0%	0%	10% lane miles
Mean MP =	56%	34%	21%	12%	0%	0%	20% lane miles

The computation of overall means and variances of market penetration for the different AHS2 options was then performed and a lognormal distribution fit done using the relationships described in section 4. The resulting market penetration distributions reflect both the uncertainty in vehicle capital costs and the uncertainty in market penetration given those costs. The market penetration distributions and results are summarized in table 8.

These results can be interpreted in view of the cost estimates shown in table 4 and the market penetration assessments in table 7. The AHS2 options have similar 50th percentile costs, namely, $1348, $1272, and $1229 respectively in table 4. For 20 percent lane kilometer AHS implementation, table 7 indicates a mean (equal to the median for a normal distribution) market penetration of about 27 percent (about halfway between 21 percent and 34 percent in the last line of the table) if costs were exactly $1250. Thus we *expect* a ball park number of about 27 percent or so for the options and indeed this is the case with mean market penetrations ranging from 25 to 28 percent. Similarly for the 10 percent lane kilometer case, the ball park expectation is about 15 percent which is also close to the actual result.

Table 8. Probability distribution on market penetration for AHS2 vehicle options.

20 percent AHS lane kilometers case

Lognormal fit	Mean	Std	mu	sigma	Market penetration prob <5%	prob 5-20%	prob >20%
Minimum infrastructure	25%	18%	-1.60	0.66	0.02	0.48	0.50
Vehicle intensive (DL)	26%	18%	-1.53	0.63	0.01	0.44	0.55
Infrastru intensive (DL)	28%	19%	-1.48	0.61	0.01	0.41	0.59

10 percent AHS lane kilometers case

Lognormal fit	Mean	Std	mu	sigma	Market penetration prob <5%	prob 5-20%	prob >20%
Minimum infrastructure	14%	11%	-2.18	0.69	0.12	0.67	0.21
Vehicle intensive (DL)	15%	12%	-2.10	0.67	0.09	0.68	0.23
Infrastru intensive (DL)	16%	12%	-2.06	0.66	0.08	0.67	0.25

Rather than show the 5th, 50th and 95th market penetration percentiles, table 8 instead indicates the probability that any option would have less than 5 percent (*very small*), between 5 percent and 20 percent (*small*) and greater than 20 percent (*moderate* to *high*) market penetration, using the lognormal distribution fits. The results show that for the 20 percent lane kilometer case, there is about a 0.50 probability of moderate to high market penetration in contrast to about a 0.25 probability for the 10 percent lane kilometer case. These probabilities reflect the relatively large coefficients of variation (std about 70 percent of the mean) for the AHS2 option market penetration summary indices.

Selected Sensitivity Analyses in Relation to Market Penetration

Some limited sensitivity analyses were performed regarding parameters not formally selected for analysis but still mentioned in section 3 above.

Procurement year for vehicle. If the interval over which time improvement factors or TIPs is shortened from the base case of eight years (year 2002) to fewer years such as four, the vehicle capital costs rise significantly. We would expect market penetrations to suffer accordingly. The four year case was run and the results for the lowest cost option were:

- for the 20 percent lane kilometer case, penetration probabilities of 0.83 for very small, 0.15 for small and 0.02 for moderate to high.

- for the 10 percent lane kilometer case, penetration probabilities of 0.93 for very small, 0.06 for small and 0.01 for moderate to high.

Processor costs for AHS2 options. A contrary opinion to the base case processor needs assumptions for AHS2 vehicles assumed the following relative processing requirements in terms of processing units:

ARV	1.3	processing power units
Minimum infrastructure vehicle	46.4	processing power units
Vehicle intensive dedicated lane	18	processing power units
Infrastructure intensive dedicated lane	15.4	processing power units

An analysis was run assuming the *optimistic* $500 per processing power unit (5th percentile) shown in table 3, instead of the original processor costs. The market penetration results for the lowest cost option (Infrastructure intensive vehicle) were:

- for the 20 percent lane kilometer case, penetration probabilities of 0.10 for very small, 0.62 for small and 0.28 for moderate to high.

- for the 10 percent lane kilometer case, penetration probabilities of 0.38 for very small, 0.53 for small and 0.09 for moderate to high.

A similar case was run where the unit base processor cost was assumed to be $1500 or the 50th percentile in table 3. The results for that case were:

- for the 20 percent lane kilometer case, penetration probabilities of 0.77 for very small, 0.19 for small and 0.04 for moderate to high.

- for the 10 percent lane kilometer case, penetration probabilities of 0.88 for very small, 0.11 for small and 0.01 for moderate to high.

If processor requirements and therefore costs were much higher than assumed in the base case risk analysis, the estimated probability of market penetration being moderate to high is significantly lower. It is useful to reiterate at this point that the market penetration model is somewhat coarse. Nevertheless, the base case AHS2 options for vehicles have a great deal of processing built into the vehicle rather than the roadway. Potentially, this choice of technology direction could strongly impact market penetration if such processing proved to be more expensive than originally envisioned. The possible progress in both simultaneously reducing costs and increasing the capabilities of computers, however, is noted in the costing methodology of volume 3. The costing methodology uses the conservative assumption of having only considered cost reduction trends and not capability increases as well. If capability advances were to be considered as well, perhaps even heavier processing requirements than originally assumed for AHS2 vehicles would still give probability of market penetration results similar to the base case risk analysis described in this report.

In summary, section 5 presented the main results obtained from implementing the risk analysis framework. Tornado sensitivity analysis diagrams indicated that the time improvement parameter for electronics (TIP_elec) is a key factor affecting the uncertainty of vehicle costs, and that land costs are a key factor affecting the uncertainty in roadway costs for most scenarios. Overall distributions on the cost/benefit summary indices were described and summarized in tables 4 and 5 for costs, table 6 for capacity and table 8 for market penetration. These distributions reflect risk/uncertainty via the size of the *credibility intervals* (the range spanning the 5th to 95th percentiles) for the summary indices. The market penetration distribution also produces probability estimates of *very small*, *small* and *moderate to high*, market penetrations as a function of vehicle capital cost and AHS freeway lane availability.

6. CONCLUSIONS

Major Findings

A cost/benefit risk analysis can help provide insights by showing more formally how uncertainties in key factors translate into uncertainties in summary cost/benefit indices. The focus of this risk analysis was on quantifying such uncertainty by developing probability distributions for vehicle and roadway costs, capacities and market penetrations for alternative AHS deployment scenarios. These distributions specify the risk or likelihood that costs, capacities or market penetrations could turn out to be significantly higher (or lower) than specified by a single summary best guess number or point estimate.

For vehicle costs, the risk analysis identified four key factors and systematically elicited the subjective probability judgments of a project team specialist to quantify uncertainties about these factor levels. The risk analysis revealed that the *time improvement parameter* for electronics products (the yearly discount factor used to model how economic competition lowers the initial cost of these products over time) is the most important of the factors in its effect on vehicle cost uncertainties. A lognormal distribution for vehicle costs was derived with a coefficient of variation (or ratio of the standard deviation to the mean) around 50 percent for the different scenarios. Vehicle cost percentile levels (e.g., 5th percentile level indicating a 5 percent chance of being less than that level) were tabulated to indicate a credibility interval ranging from the 5th to 95th percentiles. The ratio of the 95th to 50th (median) percentile was typically about 2.2.

For roadway modification costs, the risk analysis identified seven key factors and systematically elicited the subjective probability judgments of a project team specialist to quantify uncertainties about these factor levels. The risk analysis revealed that *land cost* is the most important of the factors in its effect on roadway cost uncertainties. A lognormal distribution for roadway costs was derived with a coefficient of variation (or ratio of the standard deviation to the mean) of less than 10 percent for the different scenarios. Special sensitivity analysis revealed that the cost comparison between a dedicated AHS elevated structure (Option 5) versus one lane automated with an added buffer lane (Option 2) depended strongly on land costs and the frequency of freeway bridge crossings per unit roadway length. Given a crossing frequency 50 percent reduced from the base case (which may have been atypically large), land cost uncertainties are significant enough so that either alternative could turn out to be the cheaper one.

For resulting capacity of an AHS2 implementation, the credibility interval (5th to 95th percentile range) was assessed to be 4500 to 7500 vehicles/lane/hr with a median estimate of 5800. If a cost/benefit focus is on the ratio of vehicle cost to capacity, the uncertainty in the vehicle cost in this analysis dominates the uncertainty in capacity in its effect on the uncertainty in the ratio.

A coarse model relating market penetration to vehicle acquisition cost and AHS freeway availability was calibrated. The uncertainties in both vehicle costs, and the market penetration given vehicle costs led to significant uncertainties in the market penetration for AHS2 scenarios. For 20 percent AHS freeway availability, the probability of moderate to high market penetration (greater than 20 percent of registered vehicles) was around 50 percent . For 10 percent availability, the probability of moderate to high market penetration was 25 percent.

In summary, it is not surprising that the risk analysis in this volume indicates notable uncertainties in indices such as vehicle costs and market penetration. At this point in time of AHS development, a risk analysis which did not show much uncertainty would not be very credible.

Although approximate, cost methodologies and risk analyses using expert judgment can help provide insight into the conditions necessary for having significant market penetration of AHS. The risk analysis methodology presented here is especially pragmatic. It utilizes a systematic protocol for obtaining expert judgments in the form of percentile assessments. It then develops tractable approximations and distribution fits based on these assessments to estimate probability distributions of interest such as those on vehicle and roadway costs and market penetrations. The relationships and approximations are used to estimate key features (such as means and variances) in a sound and effective manner even though the subjective input data by nature can not be extensive. The methodology is also generic and flexible enough to be applicable to other AHS problems having features similar to the one analyzed here.

Recommendations for Future Study

Because AHS technologies still require considerable research, the implementation scenarios analyzed in this study are somewhat speculative, and represent a best guess based on the state-of-the-art today. From this perspective, the implications of the numerical results of this risk analysis should not be overemphasized in suggesting directions for future study. However, the most important factors affecting uncertainty in cost/benefit indices in this risk analysis make intuitive sense to study further for decreasing uncertainties about costs and market penetration. More detailed modeling of the time improvement factor for electronics technologies, and market penetration as a function of vehicle costs and perceived benefits could help reduce some of the more significant uncertainties that relate especially to consumer cost.

Another way of reducing estimation uncertainty about key factors is to pool subjective probability judgments from multiple experts.[8] In this study, single specialists were elicited for each factor because of their special familiarity with the particular cost methodologies, scenario definitions, and time and budget constraints. It is also prudent to first develop a risk analysis methodology that works well with single expert assessments before moving on to the more complicated multiple expert aggregation techniques. Further study into which of these techniques is best suited to pool assessments from multiple experts in the AHS problem context would be desirable.

APPENDIX

This appendix contains further technical detail related to section 4 of this volume concerned with the development of a simplified framework delineating relationships among intermediate and summary cost/benefit factors. The discussion below concerns the development of a check on the lognormal distribution fit to cost/benefit summary indices.

The lognormal fit was felt to be the best way to estimate the so-called credibility interval (5th to 95th percentile range) of the summary indices, because it is a commonly-used flexible distribution and it is based on the mean and variance which can be computed somewhat robustly using the PT three-point approximations. However, as a partial check on the credibility interval computations for the summary indices, we made use of other approximations, which are not as good as the PT, but could at least provide a check. These approximations use formulas for:

- the mean in terms of the 5th and 95th percentiles and the *mode* (most likely value).
- the standard deviation (or std) in terms of the 5th and 95th percentiles alone.

We computed the *mode* of the summary index by using the *computed modes* of each factor for which uncertainty was assessed as factor *point* estimates. The factor modes were developed as follows. If a factor's 25th and 75th percentiles were symmetric about the 50th, we used the 50th percentile as the mode. Otherwise, we used the midpoint of the shortest of the *roughly* equiprobable four intervals: 5th-25th, 25th-50th, 50th-75th, 75th-95th. The formulas for the summary index percentiles in terms of the index mean, mode and standard deviation are:

5th percentile = (2.95*mean - 3.25*std - 0.95*mode)/2
50th percentile = 0.721*mean + 0.279*mode
95th percentile = (2.95*mean + 3.25*std - 0.95*mode)/2

(These formulas are derived from approximations cited in reference 3. While it need not follow that the mode of the summary index is obtained by using the modes of the factors, we hoped this approximation would at least provide a ball-park check on the lognormal fit.) The 5th, 50th and 95th percentile results for the summary indices using both the lognormal and mode methods were very similar with the 50th and 95th percentiles being quite close. Given both methods, the risk analysis advocates using the lognormal as the more confident fit, that is also partially checked with an approximate fit that was done without any distribution assumptions.

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Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Review of Studies on Automated Highway System Benifits and Impacts

U.S. Department of Transportation
Federal Highway Administration
Publication No. FHWA-RD-95-160
March 1995

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

REVIEW OF STUDIES ON AUTOMATED HIGHWAY SYSTEM BENEFITS AND IMPACTS

for
Federal Highway Administration
Precursor Systems Analysis of Automated Highway Systems
Activity Area p: Preliminary Cost/Benefit Factors Analysis

Volume VI

June, 1994

Siddharth Chandramouli
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ABSTRACT

This document summarizes research studies on Automated Highway System (AHS) benefits and impacts. These summaries will be used as background for assessing the benefits and impacts of AHS system configurations, as part of the FHWA Precursor System Analysis program.

The document is divided into two chapters, first covering completed reports, and second covering interim findings presented at the PSA workshop, held in Washington, D.C. in
April, 1994.

TABLE OF CONTENTS

CHAPTER 1: COMPLETED REPORTS

The following results come from completed reports on AHS benefits and impacts. These reports vary considerably in detail, with some providing quantitative results, others providing methodologies for impact assessment, and others qualitatively discussing AHS benefits and impacts.

Reports are sequenced alphabetically by author. For each report, information is provided on the following, when provided in the report:

1. SYSTEM CONCEPT

    Distribution of Intelligence (vehicles/roadside)
    Communication System
    Type of Information Communicated
    Actuators
    Sensors
    Functional Performance
    Changes to Roadway Infrastructure
    Deployment Concept
    Humans vs. Machines (roles and tasks)

2. IMPACTS STUDIED IN RESEARCH

3. METHODOLOGY

4. ASSUMPTIONS

5. FINDINGS

<u>Title</u> A Conceptual Approach for Developing and Analyzing Alternate Evolutionary Deployment Strategies

<u>Date</u> December, 1993

<u>Authors</u> Rokaya Al-Ayat and Randolph W. Hall

<u>Organization</u> California PATH

1. SYSTEM CONCEPTS

<u>Communication System</u>

Changeable message signs, Highway Advisory Radio (HAR), as precursors to AHS. Wireless communication in later deployments.

<u>Type of Information Communicated</u>

Vehicle monitoring, surveillance, general traveler information, dynamic route guidance as AHS precursors. AHS specifics not provided.

<u>Sensors</u>

Sensors that locate vehicles ahead and provide warning signals or automatically revert to a safe distance (type not specified). Also provides for automated inspection.

<u>Roadway Infrastructure</u>

- Aims for no demolition of houses or adverse impacts to neighborhoods surrounding freeways.
- Six possible scenarios involving changes to highway infrastructure include a segregated highway with platooning/free-agent flow, shared highways with barriers and platooning/free-agents and shared highways without barriers with platooning/free-agents.
- Lane barriers, entry/exit facilities and inspection facilities.

<u>Deployment Concept</u>

- Initial automation is in the form of autonomous vehicles.
- In parallel to vehicle automation, ATMS deployment would continue, providing the communication
- When the equipped vehicle population becomes sufficiently large, special use facilities may be constructed.
- Eventually, when market penetration becomes large enough, manual lanes may be fully converted to automation, further stimulating market demand.

Distribution of Intelligence	Not Discussed
Actuators	Not Discussed

Functional Performance	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The objective of this research is to develop an analytical framework for delineating and evaluating evolutionary deployment of IVHS. It aims to address technological, institutional, legislative and public acceptance issues, including time-dependencies among these factors. Among the benefit-impact attributes included in the framework are: congestion/capacity, safety, energy use, noise and air pollution, performance in weather conditions, land requirements, etc.

3. METHODOLOGY

Detailed description of five IVHS functional areas -ATMS, ATIS, AVCS, CVO and APTS is provided. A summary listing of IVHS projects in the U.S. is also given. A set of ground rules for development of evolutionary deployment strategies has been introduced. A framework is presented or developing and evaluating these strategies and include a set of performance measures against which a deployment strategy can be evaluated. Two models have been developed for the purpose: Benefit-Impact Model and Concept-to-Deployment Model. An example "basic" deployment sequence is provided, along with a discussion of enabling technologies and possible barriers to adoption. Finally, this paper provides an example of how the evaluation framework can be used.

4. ASSUMPTIONS

Most of the assumptions are those adapted from the FHWA PSA Broad Area Announcement. In addition the following assumptions are made:

- Vehicle equipment provides substantial user benefits, even where AHS is not implemented.

- Full vehicle automation requires minimum vehicle retrofit.

- Automation does not require housing demolition or have major adverse impacts on neighborhoods surrounding freeways.

5. FINDINGS

- The conceptual framework has the potential for integrating many ongoing R&D, test and implementation projects.

- Detailed inventory of the status of various IVHS efforts is required for understanding the development cycle.

- Any meaningful analysis must include the wide spectrum of organizations that are involved and interested in the implementation of IVHS.

<u>Title</u> Assessing the Safety Benefits of Automated Highways

<u>Date</u> December, 1993

<u>Authors</u> Mohammed Anwar and Paul P. Jovanis, UC Davis

<u>Organization</u> California PATH

1. SYSTEM CONCEPTS

<u>Distribution of Intelligence (vehicle/roadside)</u>

On-board and roadside computers.

<u>Communication System</u>

Communication between vehicles and roadside and between vehicles themselves. Continuous control of vehicles by means of sensors.

<u>Changes to Roadway Infrastructure</u>

Leftmost lane on the freeway is a dedicated automated lane. The automated lane may be separated from the rest of the freeway by some kind of a physical barrier with gaps.

<u>Functional Performance</u>

Spatial analysis to determine if relevant accidents were clustered near on and off ramps, an issue with important implications for automated highway design. Short headway between vehicles traveling at high speed.

<u>Humans vs. Machines (roles and tasks)</u>

Only the left (or median) lane is automated. Driver regains control when vehicle leaves automated lane.

Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Deployment Concept	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

To assess the safety consequences of mainline freeway accidents to the operation of a median automated highway lane. The accidents of interest are those in which vehicles or debris resulting from accidents in non-automated lanes are propelled across the freeway towards the automated lane. This research is aimed at identification of such accidents that may affect vehicle movement in the automated lane. It also attempts to understand the relationship between the location of such accidents and that of ramps.

3. METHODOLOGY

The data source is the TASAS database maintained by CALTRANS. Of particular interest is the data on accidents on a segment of I-10 between I-110 and I-405 between 1986 and 1987.

The aim has been to develop a method that would select relevant accidents from the TASAS database. The technique used to identify relevant accidents is based on the location fields (those that included the location fields of the left lane) of the vehicles involved in these accidents. A computer program has been written for the purpose.

Accuracy was verified by comparison with independent CALTRANS records. Cross-classification analysis was carried out by a program written for the purpose. Using the ramp milepost readings, the distance of each accident from the nearest ramp was determined.

4. ASSUMPTIONS

The highway is assumed to be partially automated.

5. FINDINGS

- Tests on validity of the technique in the specified duration and location indicate a slight (but not significant) over-prediction of accidents.
- Rear-end collisions are highly unlikely.
- Relevant accidents are more likely to occur at late night and early morning hours (possibly under the influence of alcohol).
- Wet pavements contribute to a small but significant portion of accidents.
- Relevant accidents are more clustered around ramps and freeway connectors than other accidents.
- These accidents represent a significant risk to the viable operation of an automated median lane.
- Further verification of findings is needed for a broader range of facilities with different configurations.

<u>Title</u> a Evaluating the Impact of IVHS Technologies on Vehicle Emissions using Modal Emission Model

<u>Date</u> June, 1994 (Draft)

<u>Authors</u> Matthew J. Barth

<u>Organization</u> California PATH

1. SYSTEM CONCEPTS

<u>Functional Performance</u>

Based on mathematical formulations, the intraplatoon spacing is set to one car, the length of a car is 5 m, the number of vehicle in a platoon is 20 and the vehicle free speed is 120 km/hr.

Distribution of Intelligence (vehicle/roadside)	Not Disucssed
Communication System	Not Discussed
Type of information communicated	Not Discussed
Type of sensors used	Not Discussed
Type of actuators used	Not Discussed
Changes to roadway infrastructure	Not Discussed
Deployment concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This report is concerned with evaluating total vehicle emissions associated with AHS. Air quality is believed to improve as IVHS technology improves mobility and decreases congestion. This paper is an effort to accurately predict vehicle emissions reductions due to smoother flow. However, the potential increase in demand for roadways and VKT (vehicle kilometers traveled) due to IVHS is not one of the concerns of this study.

3. METHODOLOGY.

Modal emissions data correspond to a vehicle's operational mode, e.g., acceleration, deceleration, steady state, cruise and idle. Using modal data in an emissions model is in sharp contrast to current emission inventory techniques. This study uses a power demand-based modal emissions model to estimate emission output. One of the most important aspects of this method is the design of the vehicle's emission control system using a simple thresholding technique. The emissions of carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx) are measured and correlated to demanded engine power induced under numerous operating conditions. The emission output is then approximated by a function that relates emission species output to demanded power. For this study, modal emissions data for a 1991 Ford Taurus was received from the Ford Motor Company. Several microscale simulations are carried out.

4. ASSUMPTIONS

No assumptions made with regard to the system configuration are explicitly stated. However, the analysis assumed a constant platoon size of 20 for all simulations. Emissions associated with maneuvers such as splitting and merging have been ignored for the present. The study assumes that vehicles on an AHS will be comparatively newer, so the analysis has been carried out using the emission rates of a single vehicle only, ignoring various vehicle classes.

5. FINDINGS

Major findings may be summarized as follows:

- At the same traffic flow volume of 2053 veh./hr and an average speed of 48 km/hr, the automated lane produces 50% less emissions (0.34 gm/sec.) than the manual lane (0.76 gm/sec.).

- For an emission rate of 0.76 gm/sec., the automated lane could carry twice the volume of traffic (4565 veh./hr).

- The maximum flow of the automated highway is 8286 vehicles/hour. at an average speed of 103 km/hr. This produces emissions of roughly 1.52 gm/sec.

In conclusion, an automated lane using platooning improves traffic flow by a factor of four, while emissions at maximum flow increase by a factor of two per km of highway. If automated lanes carry the same volume of traffic as the manual case, then the emission levels are reduced by a factor of two.

Title Consumer Demand for Automated Private Travel: Extrapolations from Vanpool User Experiences

Date November, 1993

Authors Nirupa Bonanno, Daniel Sperling and Kenneth S. Kurani

Organization: California PATH

1. SYSTEM CONCEPTS

Functional Performance

Assumes that comfort benefits from AHS may be similar to those from riding as a passenger in a vanpool.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The purpose of this study is to investigate the reasons for an individual's decision to ride rather than drive, and to draw appropriate extensions to a future marketplace where automated vehicles are an available mode choice.

3. METHODOLOGY

In order to establish the market potential for an automated vehicle one must estimate the number of individuals who consider the improvements in all the attributes identified to justify the greater cost of an automated vehicle. The focus of this study is on a group of individuals who are currently making, or at least have a close knowledge of, some of these same trade-offs: vanpoolers. A data sample of 350 vanpools from the San Francisco and Los Angeles areas has been used.

4. ASSUMPTIONS

Most significant assumption is that vanpool experiences can be extrapolated to AHS.

5. FINDINGS

- Strong preference among all groups to not driving.

- Demand for automation may depend on various attributes, such as safety, comfort, smoothness, ease of operation and cost.

- Statistically significant demographic variables exist in both male and female models.

- If automation technology can free drivers for other activities while improving safety, then this technology will be viewed as more valuable by consumers.

Title Feasibility Study of Advanced-Technology HOV Systems. Volume I: Phased Implementation of Longitudinal Control Systems

Date December, 1992

Authors T. Chira-Chavala and S.M. Yoo

Organization California PATH

1. SYSTEM CONCEPTS

Communication System

Ultrasonic, optical (infra-red) and radar signals.

Sensors

On-board transmitters, speedometers, accelerometers, turn angle sensors and laser systems.

Actuators

Braking and acceleration control units.

Functional Performance

In phase 2A, with a platoon of 12 and velocity of 88 kph, capacity would be 4.2 times conventional capacity. In phase 2B, with a platoon of 20 and velocity of 88 kph, capacity would be 4.2-4.6 times conventional. Acceleration and deceleration rates are .3g, and response time is .1 seconds.

Deployment Concept

Initially driver assistance devices, such as AICC, would be adopted, followed by longitudinal control systems and platooning.

Discussed under methodology

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Type of Information Communicated	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The objectives of this study are to identify strategies for early deployment of longitudinal control technologies on the highway, and to evaluate potential impacts of these strategies on traffic operation, highway capacity and traffic accidents.

3. METHODOLOGY

The approach for early deployment of longitudinal control technologies on the highway involves incremental implementation. Initially, relatively near-term driver-assisted devices such as AICC's could be adopted, and later fully automated longitudinal control systems with close-formation platooning could be demonstrated in selected facilities. The approach involves two phases.

Phase I

Vehicles on all roadways are encouraged to adopt AICCs as and when the technology becomes available. This study defines a hypothetical AICC capable of regulating vehicle speed, acceleration and headway through both vehicle and throttle controls.

Phase II

Longitudinal control systems with close formation platooning could be demonstrated in HOV lanes that have exclusive right of way and controlled access and egress. Two hypothetical system concepts are defined for evaluation in this study. In Phase-2A, vehicles have their equipment checked initially, form platoons and enter the travel lane of the transitway. In Phase-2B, wayside communication systems are required to coordinate platoon formation and dispatches.

4. ASSUMPTIONS

- Since changes in driver behavior cannot be predicted, they are not considered.

- New hazards that cannot be predicted are not considered.

5. FINDINGS

Phase I

- The hypothetical AICC could be a countermeasure for about 7.5% of all accidents that result in fatalities or injuries.

- The use of the AICC could results in increased flow rate.

- Research is needed to address liability issues.

Phase II

- Flow rate may be sensitive to platoon size.

- Additional right of way may be required.

- Research is needed in the areas of safety and human factors.

<u>Title</u> Systems Studies of Automated Highway Systems
Appendix II : Analysis of Automated Highway Systems

<u>Date</u> August, 1981

<u>Authors</u> GM Transportation Systems Center
General Motors Technical Center
Warren, Michigan 48090

<u>Organization</u> Prepared for:
U.S. Department of Transportation
Federal Highway Administration
Offices of Research and Development
Traffic Systems Division
Washington, D.C., 20590

1. SYSTEM CONCEPTS

Deployment Concept

The deployment concept consists of 3 phases of automation, consisting of increasing levels of command communication and control, both on and off-vehicle.

Distribution of Intelligence

Wayside: Medium-sized computer; controls and displays.

Guideway: Microprocessors, lateral and longitudinal benchmarks, pallet dispatch system.

Vehicles: DEPs, diagnostics

Communication System

Wayside: Microwave communication; RF of inductive link to vehicles
Vehicle-based radar and guideway reflectors, DEPs.

Type of Information Communicated

Low distribution non-quantized error signal, wayside, guideway commands

Sensors

Guideway wire and vehicle-based amplitude or phase detection, wall feelers, brake sensors, tire pressure, fuel and fluid sensors and decelerometer.

Actuators

Brakes, throttle override.

Changes to Roadway Infrastructure

Elevated guideways, partial refuge lanes, modification to existing structures, snow melting systems, paving, entry/exit equipment and maintenance facilities.

Functional Performance

Aerodynamically designed vehicles with a drag coefficient of .4. Estimated increase in vehicle weight of 10 kg. A capacity of 1800 - 3300 vehicles/hour per lane, with a speed of 54-108 kph.

Humans vs. Machines (roles and tasks)

Driver initiated and supervised merging and diverging (Phase I). Increasing levels of automation and fewer driver responsibilities, except during the transition to non-automated mode (Phases 2 and 3).

2. IMPACTS STUDIED IN RESEARCH

The purpose of this AHS analysis report is to document a selected set of automated highway concept designs, a compatible set of system deployment strategies, urban and intercity environments, and the results obtained from analyses of AHS deployments which were synthesized from these characteristics.

The focus of this document is to review the results of previous efforts, and establish a final set of system concepts and implementation plans, develop a set of system building blocks from which various system concepts can be synthesized for cost evaluation, and analyze the system deployments in both urban and intercity environments to obtain a reduced set of alternatives for further analyses.

3. METHODOLOGY

A deployment area analysis is conducted to determine the relative merits of AHS system deployment in urban and intercity environments. Summary system concept descriptions are presented along with a set of subsystem technologies to perform the system central, wayside and guideway and vehicle functions. Several technological issues are resolved. Performance analysis and reliability analysis have been carried out to establish energy consumption characteristics and address the issue of AHS feasibility.

A review of the system implementation strategies is conducted and the institutional, operational and financial aspects of the implementation issues and options are presented. This is followed by developing system building blocks to represent real world conditions. The results of the system analyses are presented followed by general conclusions which influence the nature of the system trade analysis.

4. ASSUMPTIONS

- User cost associated with AHS is assumed to be $0.03/km greater than highway cost.

- After year 23, the fleet is assumed to consist entirely of AHS-ready vehicles.

5. FINDINGS

- Urban-average deployments provide much better utilization statistics than urban-smart deployments and intercity cases.

- The high cost of AHS is likely to deter the non-business intercity traveler.

- Life cycle cost analyses indicate that smart intercity cases are less expensive than average intercity cases. However, urban values provide mixed results.

- Normalized EUAC values indicate that smart deployments are less expensive than average deployments on a per lane km basis and range from $80,000 to $219,000 for smart intercity deployments and from $109,000 to $254,000 for smart urban deployments.

- Average systems in 1990 are estimated to have a maximum capacity of 2927 veh./lane/hr. and smart systems a capacity of 2405 veh./lane/hr.

6. DATA THAT MAY NEED TO BE UPDATED

- Estimated number of daily person trips in 1990.

- Estimates of capacities in future time frames.

- Costs related to wages, infrastructure, labor and maintenance, control and command technology.

- Assumptions of available technology for DEPs and AHS in general.

- Revision of 40-year forecasts and EUAC/NPV assessments of smart vs. average deployment concepts.

Title Systems Studies of Automated Highway Systems
Appendix III : AHS Trade Studies (Final)

Date August, 1981

Authors GM Transportation Systems Center
General Motors Technical Center
Warren, Michigan 48090

Organization: Prepared for
U.S. Department of Transportation
Federal Highway Administration
Offices of Research and Development
Traffic Systems Division
Washington, D.C., 20590

1. SYSTEM CONCEPTS

Deployment Concept

The deployment concept for guideway operation is: a first stage where contract operation is the modus operandi at the request of the state itself, and the second stage where the state wishes to do its own operation. The tasks recommended for an orderly deployment of an AHS are: identification of technological developments, product development program, system deployability analysis, prototype test, selection of initial deployment area, detailed area analysis, and deployment system design and consideration.

Functional Performance

The velocity on all parts of the AHS is set at 110 kph.

Distribution of Intelligence	All Factors Discussed in Detail in Appendix II of Report
Communication System	
Type of Information Communicated	
Sensors	
Actuators	
Changes to Roadway Infrastructure	
Humans vs. Machines	

2. IMPACTS STUDIED IN RESEARCH

The focus of this research is to establish preferred system states for the AHS concepts and implementation plans through the trade analyses of selected system parameters. The results are used to determine whether significant advantages can result from modifications of the socio-politico-economic, operational, and/or deployment parameters without unduly compromising the system measures.

Socio-Political-Economic Considerations
This section discusses the institutional, legal/regulatory/legislative, environmental/community impact, user acceptance and financial issues.

Operational Considerations
This section examine the sensitivity of the AHS costs and deployment characteristics to changes in selected operational characteristics and parameters to determine the impact of the changes on the system measures. The characteristics under study are velocity sensitivity, entry/exit delay sensitivity, the "smart vehicle" concept, increased user subsidy and operational implementation considerations.

Deployment Considerations
This section concentrates on areas of the AHS that are highly dependent on issues related to size and function of fixed facilities and equipment and location when provided for a deployed system. Among the considerations are: facilities and equipment cost reduction, urban and intercity deployment, lane conversion alternatives, land area requirements, concept phasing, phasing, phasing of automation, deployment staging and reliability enhancement.

3. METHODOLOGY

Socio-political-economic impacts are classified as sensitive and non-sensitive issues. Non-sensitive issues are addressed by providing a recommendation way to deal with the problem during implementation. On the other hand, issues that are sensitive to the deployment strategy chosen are identified and the consequences of various technological decisions are presented and tested.

Operational issues such as velocity sensitivity, entry/exit delay sensitivity etc., are addressed by carrying out a present value analysis of the respective sensitivity study.

Deployment issues such as facilities and equipment cost reduction are addressed by means of a preliminary cost analysis where two cost categories, namely guideway construction and vehicle/DEP were identified as having significant cost reduction potential.

4. ASSUMPTIONS

- Energy cost has an assumed annual cost of $0.0445.

- DEPs require a processing time of about 60 seconds at both entry and exit points.

- The guideway is assumed to be electrified concurrent with guideway construction.

- DEPs are used by all vehicles throughout the life of the AHS rather than being phased out eventually.

- Both electrified and non-electrified vehicles are assumed to operate on the AHS within eight years of opening.

- A lower bound has been provide for the cost of lane conversion option of automated freeways by assuming merely a resurfacing of existing roadways.

5. FINDINGS

- Operation of the guideway is greatly influenced by factors such as level of vehicle intelligence, phasing of automation, guideway electrification and DEPs.

- Operating and maintenance cost recovery may be more feasible in the hig her use urban areas.

- Increased velocity makes AHS more attractive, though energy costs increase substantially.

- Use of DEPs significantly increase user costs.

- AHS land area requirements are such that more land is necessary exactly where less land is available.

6. DATA THAT MAY NEED TO BE UPDATED

Given that this research was carried out in 1981, the data and forecasts made in the calculations/analyses may need to be updated.

- Assumptions of available technology for DEPs and AHS in general.

- Forecasts of air-quality levels during the '80s an the '90s.

- Estimated incremental costs for AHS-ready vehicles ($2000-$2500 is the cost mentioned)

- Revision of 40-year forecasts of AHS operating and maintenance costs, interest rates and inflation rate used in the net present value/annual cost analyses.

Title	Longitudinal and Lateral Throughput on an Idealized Highway
Date	October, 1993
Author	Randolph W. Hall
Organization	California PATH

1. SYSTEM CONCEPTS

Functional Performance

Parametric analysis over a range of speeds, traffic densities and trip lengths.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH.

- Potential increase in highway capacity due to automated highways.
- Effect of trip length distributions on the lane "flux".
- Conditions where lane changes have an appreciable impact on capacity.
- Effects of design parameters (pertaining to the execution of lane change maneuvers) on capacity.

3. METHODOLOGY

General

A throughput model of a multi-lane AHS with lane changes is developed to account for trip length distributions and their effect on "flux". To illustrate fundamental principles, the model is applied to an idealized highway operating under stationary conditions, which could be extended to non-stationary conditions. Parametric analysis is used to study the effects of design parameters on capacity.

Workload/Throughput Model

A traffic-flow model is developed that relates lane flow to "lane flux". The space occupied by an individual vehicle is modeled, both for a purely longitudinal and a lane change mode. These two models are then combined into a "workload" model. This model forms the objective function for an optimization model which maximizes throughput through control of lane change behavior.

Optimization is facilitated by the theorem that states that "there exists an optimal solution to the following property: all trips assigned to lane i have equal to or greater length than all trips assigned to lane i-1, for all i greater than or equal to two."

Parametric Analysis is coupled with the optimization scheme and applied to trip length distributions. The deterministic and exponential distributions are used as upper and lower bounds on trip length entropy.

4. ASSUMPTIONS

Access and egress to the AHS are assumed to occur only through the right-hand lane and are located continuously over the entire length of the highway. The AHS is assumed to be of the non-mixed, multiple-lane type.

5. FINDINGS

- For the idealized model, conditions under whi ch lane changes result in a substantial decrement in capacity are identified, based on the "ratio of incremental lateral requirement to longitudinal requirement, per unit flow" (beta).

- When beta > 0.3, the capacity of a multi-lane AHS becomes comparable to that of a conventional highway.

- For cited capacity values, queuing for lane changes would be substantial.

- Idealization does not account for spatial and temporal variations in flow and flux. This could be achieved by considering a non-linear multi-commodity flow formulation.

- Unclear whether the discrete nature of highway entrances and exits substantially alters highway capacity.

- Space requirement on right-most lane may be higher than indicated in the report.

Title	Time Benefits of New Transportation Technologies: The Case of Highway Automation
Date	June, 1991
Authors	Randolph W. Hall
Organization	California PATH

1. SYSTEM CONCEPTS

Functional Performance

Parametric analysis for a range of highway capacities.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of information communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to roadway infrastructure	Not Discussed
Deployment concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This paper examines the role of travel time in the choice of transportation technologies and investigates how new technologies - highway automation in particular - can allow us to reduce travel time in the future.

3. METHODOLOGY

This paper begins with an examination of travel time in technological choice. The focus shifts to highway automation. A hierarchy of automation schemes is created, and the time benefits of each are discussed. Finally the effects of automation on highway performance are modeled and evaluated, first examining the space efficiency of highways, then measuring the benefits of increased capacity and increased velocity.

4. ASSUMPTIONS

- Travel behavior is influenced by the introduction of automation, which may affect AHS benefits.

- The initial niche for highway automation is likely to be in densely developed cities where expansion opportunities for conventional highways are limited.

5. RESULTS

- Even simple forms of highway automation can provide substantial travel time benefits.

- Automated low-speed and stationary merging can reduce queuing.

- "Mini-highways" can reduce delays crossing urbanized areas.

- "High-speed highways" can make long-distance travel faster.

- Any move toward automation must be considered in the light of alternatives such as car-pooling and mass transit.

Title	Casualties in Accidents Occurring During Split and Merge Maneuvers
Date	November, 1993
Authors	Anthony Hitchcock.
Organization	California PATH

1. SYSTEM CONCEPTS

Functional Performance

Intraplatoon spacing of 1 m and interplatoon spacing of 80m at a velocity of 108 kph.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This report is concerned with one aspect of follower's collisions, namely the situation where any failure is to "brakes-on". The objective is to design the brake control system in a way that the impact of a deleterious failure on casualties is reduced.

3. METHODOLOGY

The probabilities of death or injury arising from a "fail-safer" brake failure (to brakes-on), while split and merge are taking place have been calculated. The basic method has been discussed in Hitchcock (1992).

4. ASSUMPTIONS

Average platoon size of 8 and a mean journey length of 24 km and a velocity of 108 km/hr. and a mean automated kilometers traveled of 12,000/year per vehicle. Intra-platoon spacing of 1 m, and an inter-platoon spacing of 80 m.

5. FINDINGS

- Under certain conditions of reliability, the merge maneuver introduces unnecessary danger into the AHS operation. Alternatives have been described that avoid these dangers.

- The split maneuver is not dangerous in itself.

- The mean time between failures of the vehicle control system should be at least 10^6 hours to ensure AHS reliability.

Title Methods of Analysis of IVHS Safety

Date December, 1992

Authors Anthony Hitchcock

Organization California PATH

1. SYSTEM CONCEPTS

Distribution of Intelligence (vehicle/roadside)

Mainly vehicle-borne intelligence, with a small amount of intelligence incorporated into the infrastructure for reasons of safety. Control systems to maintain vehicle position in platoon.

Sensors

Vehicle presence detector to sense when a vehicle is present.

Actuators

Engine torque, vehicular speed, etc. may react to information provided by sensors (for e.g., angle of throttle pedal).

Changes to Roadway Infrastructure

Some special physical infrastructure is necessary. For safety reasons, automated lanes are separated from each other, and from the rest of the freeway by a small barrier.

Communication System	Not Discussed
Deployment Concept	Not Discussed
Functional Performance	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed
Type of Information Communicated	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This research has as its field the safety of IVHS devices in areas which are relevant to PATH. These include automated freeways. Investigation of capacity features of a properly designed AHS has the highest priority.

3. METHODOLOGY

In order to analyze the safety of IVHS devices, two major problems have to be overcome: specifying a safety criterion for an automated freeway and designing an automated freeway which fulfills such a criterion, and second, validation of such a design. The problems have been solved by means of a demonstration - two such designs have been constructed and both have been verified using the complete specification method and a technique called fault tree analysis. In order to study the safety considerations of driver aids and copilots, "in-depth" accident databanks were employed. Due to the difficulty in obtaining data, alternative evaluation techniques and sources of data are being explored.

4. ASSUMPTIONS

Though not stated explicitly, it is assumed, based on the recent work on automated freeways, that it is possible to design an automated freeway which conforms to a reasonable safety criterion. Further assumptions include: partial automation of freeway lanes, lanes not restricted by "end-to-end" travel and the presence of lateral steering.

5. FINDINGS

- It is possible to design an automated freeway which meets rational safety criteria, though an idealized freeway is infeasible.

- A technique has been developed and demonstrated to ensure that a design meets the chosen safety criterion.

- Safety considerations constrain design considerably.

- Techniques are described which estimate the net safety impact of devices. Databanks need to be explored.

Title: A Continuing Systems-Level Evaluation of Automated Urban Freeways: Year Three

Date: October, 1993

Authors: Robert A. Johnston and Raju Ceerla

Organization: California PATH

1. SYSTEM CONCEPTS

Functional Performance

Various scenarios are studied, with velocities ranging from 96-130 kph, and lane capacities of 3,600 to 7,200 vehicles per hour.

Deployment Concept

Alternatives include deployment on HOV (high-occupancy-vehicle) lanes, partial automation of freeway links, and full automation of freeway links.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

Travel and emission impacts of urban freeway automation scenarios, compared to travel demand reduction scenarios, such as travel pricing and land use intensification.

3. METHODOLOGY

General

The Sacramento Regional Transit Systems Planning Study Travel demand model of 1989 was adapted for AHS analysis. This model consists of the four typical UTPS steps: (1) Trip Generation, (2) Trip Distribution, (3) Mode Choice, and (4) Trip Assignment.

System characteristics were varied to analyze various scenarios. These characteristics include capacity, headway, travel, cost, highway and transit configuration and attributes, land use distribution and other relevant factors.

Trip Generation

In the first step of the 4-step UTPS process, trip production and attraction rates are generated based on the 1968 SATS trip generation model, the 1984 SACOG Metro Study and the 1990 RT Planning Systems Study model.

Trip Distribution

The data generated in the Trip Generation Model was used to distribute trips to the 812 zones using a standard gravity model equation. The travel Impedance matrix was generated initially using uncongested speeds and then a feedback process was employed. Friction factors were used to represent the likelihood of travel between zones based on the impedance factors between the zones.

Mode Choice

Mode choice models were developed for the 1989 Systems Planning Study for two sets of trips, home-based trips and non-work trips. These have been adopted in this research. The home-based trip is a multinomial logit model (MNL). The non-work trip mode split estimation process involves factoring applied to home-based work trip transit shares estimated from the MNL HBW model.

Traffic Assignment

The study is based on the traffic assignment process done by MINUTP. The number of iterations used in the Systems Planning Study was 5 and this has been maintained in this study. The path building process involves the use of travel impedances of the links; this is actually a feedback process. Highway assignment uses the "equilibrium assignment process".

Overall Model Operation Methods

When a driver picks a route to get to his destination, he would select the minimum path based on travel time. Every other driver does likewise, after which the network may become congested. Then the driver goes through the process all over again. This procedure is a dynamic and continuous process and ends when the driver's speed has reached an optimal value with respect to assignment of the whole network. In the trip distribution process, the feedback goes to the trip distribution step, as well as the mode choice step. The principle is the same as that of the mode choice feedback loop.

Model parameters are calculated using the adjusted daily load network. The model also estimates the person trips by trip purpose and vehicle trips by mode.

The 2010 No-Build option was the base network. The study area was the Sacramento RT Systems Planning Study. The updated 1989 and year 2010 land use and socioeconomic data were used.

Existing alternatives modeled were: 1. 1989 Base Year Model, 2. 2010 No-Build Model, 3. HOV lanes, 4. LRT (light-rail-transit) alternatives. Automation alternatives modeled were: 1.

HOV1 (HOV lanes automation at 96 kph/1 sec. headway/3600 veh. per hr. per lane), 2. HOV2 (HOV lanes automated at 130 kph/0.5 sec. headway/7200 veh. per hr. per lane), 3. AUTO1 (Partial automation on general lanes using 2010 no-build alternative), 4. AUTO2 (Partial automation general lanes automated - 130 kph/0.5 sec. headway), 5. AUTO3 (All lanes automated - 96 kph/1 sec. headway). In addition, road pricing and transit-oriented-development (TOD) alternatives were modeled.

4. ASSUMPTIONS

Discussed in methodology.

5. FINDINGS

- For alternative HOV1, vehicle km travel ed (VKT) increased by 2.8% and vehicle hours of delay (VHD) increased by 11.2%.

- For HOV2, VKT increased by 3.4% and VHD increased by 16%.

- Comparison of freeway automation alternatives showed that total delay declined in all alternatives except HOV1 and HOV2.

- Comparing full feedback to partial feedback, VKT decreases by 11.3% for partial automation, VKT decreases by 12.2% for full automation (130 kph). Average trip length decreases by 11.5% (partial), 12.75% (full-96 kph) and by 12.17% (full-130 kph). VHD decreases by 39.3% for partial, 46.2% for full (96 kph) and 45.2% for full (130 kph).

- Greatest reductions in VHD are found in the TOD and no-build alternatives.

- LRT has lower VKT than pricing under full automation.

- Full feedback reduced the percentage of transit trips for all scenarios.

- Increased VKT may lead to increased vehicle emissions.

- Congestion pricing reduces peak-hour auto volumes and increase speeds and VKT slightly.

Title Automating Urban Freeways: Policy Research Agenda

Date February, 1989

Authors Robert A. Johnston, Mark A. DeLuchi, Daniel Sperling and Paul P. Craig

Organization UC Davis

1. SYSTEM CONCEPTS

Automation consists of 3 sets of technologies, (1) navigational information, (2) automated lateral control and (3) longitudinal control.

Distribution of Intelligence

On-board and roadside computer control; roadway computers coordinate with participating vehicles.

Communication System

Type of Information Communicated

Sensors

Radar-like system to sense vehicles in front.

Actuators

Automated braking and acceleration.

Deployment Concept

Gradual deployment in phases to minimize disruption to existing transportation network.

Stage I:	Voluntary onboard navigation and route guidance devices.
Stage II:	On-board longitudinal control.
Stage III:	Lateral control and dedicated lanes.
Stage IV:	Full automation of some lanes.
Stage V:	Full automation of all lanes.

Functional Performance

Urban freeway system with dual mode planning at speeds of up to 160 kph and headways of 0.3 seconds.

Human vs. Machine Roles and Tasks Not Discussed

2. IMPACTS STUDIED IN RESEARCH

Identification of research issues important to the development, implementation and acceptance of freeway automation. Systems-level effects of automation on pricing, traffic congestion, air pollution, noise, safety, pricing and equity. Emphasis on private auto and truck trips.

3. METHODOLOGY

Lays out a research agenda with issues that need to be addressed before or during automation based on studies done previously.

4. ASSUMPTIONS

No freeway or ramp-lane additions assumed in order to examine the pure automation case.

5. FINDINGS

- Unclear that capacity can be increased unless arterials and ramps are expanded.
- Ways of screening non-automated vehicles need to be examined.
- Increasing freeways will result in a higher VKT and more air pollution and noise.
- Freeway sound walls, engine design need investigation.
- Unclear if safety will improve due to potential problems with vehicles, drivers, roadways and weather.
- Economic efficiency needs to be addressed.
- Privacy concerns are critical.
- Sharing and planning between private and public bodies needs to be studied.

Title Highway Electrification and Automation Technologies- Regional Impacts Analysis Project

Date November, 1993

Authors Mark A. Miller, et.al.

Organization California PATH, Southern California Association of Governments (SCAG)

1. SYSTEM CONCEPTS

Type of Information Communicated

Speed control, signal control, electronic route guidance, automatic trip routing and scheduling pre-trip electronic planning and on-board navigation systems.

Sensors

Longitudinal control devices include collision avoidance enable the vehicle to sense relative distance and velocity, such as radar obstacle detection.

Actuators

Automatic braking headway keeping and automatic steering are among the actuator functions.

Changes to Roadway Infrastructure

Lane separation for maximum safety. Special egress and access facilities provided. The transportation system involves roadway powered vehicles that transfer power from electric cables buried under surface roadways. Energy is provided by means of an inductive coupling system. Additional ramps are added in some cases for automated vehicles.

Deployment Concept

Automated braking, headway keeping, automatic steering and communication systems are component features of the fully automated system.

Functional Performance

Vehicles travel in fifteen vehicle average length platoons at approximately current free flow speed limits on freeways, resulting in a capacity of 6,000 vehicles per lane per hour.

Distribution of Intelligence	Not Discussed
Communication System	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

Applications of highway automation and roadway electrification have been designed and evaluated for portions of the freeway system in the greater L.A. region. For highway automation, mobility was the primary impact, although ramifications of this technology on air quality were also examined. The impacts of highway automation and roadway electrification were investigated to determine the extent to which these advanced technologies could alleviate congestion and pollution.

3. METHODOLOGY

The SCAG Regional Transportation Model System was employed to generate the baseline assessment of travel in 2025. Population and employment forecasts were developed for use in transportation analysis. A baseline forecast was developed for electricity requirements and capacity in the year 2025 for this study by Cambridge Systematics. The forecast was derived from the information supplied by the California Energy Commission.

A modeling framework was designed for evaluating the application of roadway electrification and highway automation to selected freeway lanes. System usage analysis evaluated the market potential number of trips and corresponding VKT. The two automation scenarios developed in this research are referred to as base network ramps and additional ramp facilities.

4. ASSUMPTIONS

The freeway automation technology was assumed to require lane separation to ensure maximum safety. RPVs and EVs will be developed simultaneously. The increased electricity demand would not require additional power plant capacity. The planning model does not provide feedback, unlike the Johnston research.

5. FINDINGS

Results depended on the specific design considerations imbedded in each technology scenario.

Highway Automation

- Congestion mitigation occurred on both automated and mixed flow lanes and significant mobility improvements were observed.

- Mobility deterioration was exhibited on existing freeway ramps.

- Enhancements are needed to the current simulation m odel.

Roadway Electrification

- Sizable air quality improvements and petroleum usage reductions were predicted.

- Increased electricity demand for RPEVs was found to be negligible.

- Evidence of electromagnetic field exposure was negligible.
- Acoustic measurements were high enough to warrant further testing.
- RPEVs may offer some economic advantages compared to conventional vehicles.
- Further research is needed for impacts assessment.

Title	Potential Benefits of Roadside Intelligence for Flow Control in an IVHS
Date	January, 1993
Authors	B.S.Y. Rao and P. Varaiya
Organization	California PATH

1. SYSTEM CONCEPTS.

Distribution of Intelligence (vehicle/roadside)

Roadside and on-board computers.

Communication System

The proposed SmartIVHS achieves high throughput and safety through a three layer control hierarchy distributed between vehicles and infrastructure.

Type of information communicated

Destination, lane change positions and path are communicated by roadside computer to vehicle.

Actuators

Electronic steering, throttle and brake actuators.

Functional Performance

A typical scenario involves a platoon size of 15, intra-platoon distance of 2 m, inter-platoon distance of 60 m, vehicle length of 5m, speed of 72 km/hr resulting in a maximum steady state flow of 6000 vehicles/hr.

Humans vs. Machines (roles and tasks)

Driver announces entry/exit by voice or keyboard entry.

Sensors	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed

2. IMPACTS STUDIED IN RESEARCH.

This paper reports a design of the flow control function of the highly automated Intelligent Vehicle Highway System, denoted by the authors as SmartIVHS. SmartIVHS achieves high throughput and safety through a three-layer control hierarchy distributed between the vehicle and the infrastructure. Previous work was devoted to the two lowest layers. This paper considers the third or "link layer" which controls the vehicle stream based on the aggregate traffic variables. Its objectives are to maximize throughput and to maintain smooth traffic flow.

3. METHODOLOGY.

The structure of the link layer controller is proposed. The objectives are met by proper guidance of the lane changing behavior and speed of the vehicle. Performance of the link layer controller is evaluated using a fluid flow simulator, SmartLink. Two cases were considered. In the first, vehicles entering the highway had exits evenly distributed among those available. In the second, one tenth of all vehicles attempt to exit at a particular location, corresponding to traffic bound for a major sporting event.

4. ASSUMPTIONS

Traffic is assumed to operate under automatic coordinated control, and is modeled as a compressible fluid. The authors assume that the control laws can be applied to scenarios that are more general than those used in the simulation.

5. FINDINGS

- In both cases the throughput is at least twice as high as an equivalent highway with manually controlled vehicles.

- The maximum loss in throughput without adaptive routing when the inside lane is blocked is about 25%. This can be further reduced with adaptive routing.

- The expected delay for a traveller can be reduced by over 50%.

- In some cases the use of adaptive routing increases the number of vehicles that tend to miss their exits.

- Experiments show that roadside controllers works satisfactorily though more testing is required.

- Through deployment of roadside controllers, simple regulation and control policies can reduce delays significantly.

Title Investigations into Achievable Capacities and Stream Stability with Coordinated Intelligent Vehicles

Date January, 1993

Authors B.S.Y. Rao, P. Varaiya, and F. Eskafi

Organization California PATH

1. SYSTEM CONCEPTS

Sensors

Line-of-sight devices with ranges of 60 to 80m with a maximum sensing delay time of 0.1 s.

Actuators

Braking actuators with a delay time of 0.2 s.

Functional performance

Rates of acceleration and deceleration vary enormously with road condition, tire condition and weather. For comfort, maximum acceleration and deceleration are limited to 0.2g and -0.5g respectively. Speed is expected to vary from 24 m/s to 28 m/s. Inter-platoon spacing ranges from 25 m to 35 m while intra-platoon spacing is set at 1 m with a maximum platoon size of 20.

Humans vs. Machines (roles and tasks)

Control transfers to driver on exiting the automated highway.

Distribution of Intelligence	Not Discussed.
Communication System	Not Discussed.
Type of Information Communicated	Not Discussed.
Changes to roadway infrastructure	Not Discussed.
Deployment concept	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This paper attempts to determine achievable capacity of an IVHS. It is recognized that in an IVHS where steady-state flow has been reached, entrance and egress of vehicles will be the primary cause of traffic stream disturbance and that ultimately this will dictate the flow rates which can be sustained reliably. Thus this study concentrates on entrance and egress strategies.

3. METHODOLOGY

A detailed simulator, SmartPath, which models the passage of individual intelligent vehicles along the highway, is employed. This simulator allows the examination of transient behavior of the traffic stream under various conditions. Three different strategies for allowing vehicles to enter and leave automated lanes are examined. The corresponding maximum flow rates are measured. The time taken by vehicles to enter an automated lane and thereby the time taken to build up high flows is recorded. Finally, the effects on flow of vehicles leaving an automated lane are measured. It is shown that this would be the major source of traffic stream disturbance.

4. ASSUMPTIONS

It is assumed that all vehicles are equipped with at least the technology to perform Autonomous Intelligent Cruise Control (AICC). Certain other assumptions on the behavior of the automated vehicles:

- Platooning is possible only in the automated lane.
- Vehicles are able to communicate occasionally with each other to perform maneuvers and also frequently with each other when entrained as platoons.
- Each driver activates his automation equipment at the earliest op portunity (possibly the transition lane) to ensure that vehicles enter the automated lane as soon as possible.
- Vehicles in the transition lane follow the control law which keeps the vehicle at the defined target speed and at a safe distance from the vehicle in front.
- Vehicles travel on the automated lane until close to their exit, when control is passed back to the driver.

5. FINDINGS

Three different policies governing entrance to and egress from the automated lane are examined by altering the logic of SmartPath, using the basic merge, split and change lane maneuvers:

Case 1: Although high flows can be maintained, rider comfort is low due to frequent deceleration and acceleration. This causes a large change in headway, though this is merely a transient. High on-ramp flows of up to 1800 vehicles/hr can be supported. Vehicles leaving the automated lane cause large disturbances. An egress demand rate of only 900 vehicles/hr causes a 25% drop in flow.

Case 2: Platoons deviate from optimal speed less often and with less magnitude. High flows are achieved and high on-ramp flows are maintained. Egress of vehicles causes a large drop in flow.

Case 3: Egress is very small. High flow rate is achieved with a peak of about 6000 vehicles/hr. Vehicle entry and egress are very rapid.

<u>Title</u> Flow Benefits of Autonomous Intelligent Cruise Control in Mixed Manual and Automated Traffic

<u>Date</u> January, 1993

<u>Authors</u> B.S.Y. Rao and P. Varaiya

<u>Organization</u> California PATH

1. SYSTEM CONCEPTS.

<u>Sensors</u>

Sensors have a 60m range.

<u>Deployment Concept</u>

A single manual lane contains AICC areas where vehicles can activate AICC and form platoons. In addition, there is a transition lane with several entrance ramps. In simulation experiments, entrances are spaced 1 km apart.

<u>Functional Performance</u>

Flow is restricted to 1,800 vehicles/hr in the manual part of the inside lane, with random headways. The inside lane has a maximum capacity of 6,900 vehicles/hr.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of information communicated	Not Discussed
Actuators	Not Discussed
Changes to roadway infrastructure	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH.

This research examines the potential flow increase when only a proportion of vehicles on a highway are equipped with AICC.

3. METHODOLOGY.

A theoretical upper bound is derived on the capacity gained using AICC for various degrees of market penetration. This bound is found to be inaccurate for high flows, so the model is extended to deal with high demand cases. Finally, the results of a simulation in which the behavior of vehicles is modeled at a detailed level are described. Results are provided for achievable capacities and stream stability.

4. ASSUMPTIONS

- All vehicles equipped with AICC form platoons with leading vehicles once detected, and after they have entered the automated section.

- There is no limit on potential platoon size.

- In the improved model, it is assumed that certain vehicles in the inside lane are equipped with AICC.

- In the simulation experiment, it is assumed that a driver in the transition lane who is adjacent to a platoon and wants to enter the inside lane will take positive action and decelerate to join the platoon.

5. FINDINGS

Estimates for maximum capacity increases using both theoretical models and the SmartPath simulator agree when the level of penetration of AICC technology is under 40%, but at higher levels of penetration, the theoretical model overestimates the capacity increase. Using published values of AICC control strategy, it is found that the AICC lane can achieve a maximum flow of 5500 vehicles/hr. However, the effective flow is reduced to 2700 vehicles/hr as it is not possible to have any permanent flow in the transition lane simultaneously.

The inter-vehicle spacing of 8 m is, in the authors' opinion, too small for a variety of reasons. In general, AICC can offer modest improvements to lane capacity at low market penetration levels and probably has a beneficial, if slight, effect on stream stability. At higher levels of implementation, greater increases in capacity become harder to achieve due to stream instability and limits on the rates at which vehicles can be fed into highways. Though the results show that AICC leads to significant gains in capacity, certain highly unrealistic assumptions (in the opinion of the authors themselves) have been made to achieve these benefits.

Title	Potential Contributions of Intelligent Vehicle/Highway Systems (IVHS) to Reducing Transportation's Greenhouse Gas Production
Date	August, 1991
Author	Steven E. Shladover
Organization	California PATH

1. SYSTEM CONCEPTS

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Functional Performance	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The purpose of this paper is to remove some of the misconceptions associated with IVHS technologies and to qualitatively explain how the impact of transportation on global warming can be substantially reduced.

3. METHODOLOGY

The paper discusses the potential impact of IVHS on global climate change in qualitative terms. The place of IVHS relative to other elements of the transportation-global climate change "system" is illustrated schematically. The specific ways in which IVHS technologies influence the supply and demand sides of road transportation are discussed. The concept of the performance "envelope" (which is commonly applied to aircraft technologies) can be extended to transportation systems. The contributions of IVHS in ameliorating global warming are explained by considering the supply and demand sides of the ground transportation system.

4. ASSUMPTIONS

Due to qualitative nature of paper, there are no specific assumptions.

5. FINDINGS

- Attempts to reduce the transportation system's contribution to global warming are somewhat in conflict with economic development and people's desire for mobility. This can be eased by technological improvements.

- An integrated approach is essential to solving the problems of safety, congestion, energy, air quality and global climate change.

- The paper emphasizes the need for "broad-scale system thinking", to rationalize the regulatory and market incentives, and thereby develop solutions that make sense.

<u>Title</u> The Automated Highway System (AHS): Concepts Analysis

<u>Date</u> August, 1993

<u>Authors</u> William B. Stevens

<u>Organization</u> MITRE

1. SYSTEM CONCEPTS

<u>Distribution of Intelligence (vehicle/roadside)</u>

Subordinate control from road-side, autonomous control by vehicles or combined control.

<u>Communication System</u>

Vehicle must provide for installation of electronics and antennae for interacting with wayside and vehicles, interface with sensors and actuators and other components.

<u>Type of Information Communicated</u>

Passive/active indication of lane boundaries, sensing of obstacles, connectivity for entering and exiting vehicles, command and control etc.

<u>Sensors</u>

Sensors and diagnostics to detect malfunctions: longitudinal, lateral and lane boundary sensors.

<u>Actuators</u>: Not discussed.

<u>Roadway Infrastructure</u>

Provision for electric power, passive markers (center magnets), passive barriers, active markers, freeway-type surface, pallet attachment to vehicle or a special pallet.

<u>Deployment Concept</u>

The eventual AHS deployment will probably be a combination of the various alternatives discussed in the report.

<u>Functional Performance</u>

The vehicle is capable, as it is produced, for fully automated operation on a standard AHS roadway, is capable of being upgraded or is incapable of such functions. These are the broad types of vehicles which will be needed.

Humans vs. Machines (roles and tasks)

Cooperative intelligent cruise control, smooth transition to and from an instrumented roadway. with proper check-in, check-out and driver alert.

2. IMPACTS STUDIED IN RESEARCH

This report defines a process by which concepts can be defined; and using that process, postulates a set of AHS concepts for use in defining the AHS concept modeling and simulation capability.

3. METHODOLOGY

The approach is to define the AHS goals and subgoals; define the characteristics that distinguish one AHS concept from another; define an initial set of AHS concepts using the concept definition factors and examine the potential for combining some of these factors.

4. ASSUMPTIONS

Variations in three AHS components: entry and exit infrastructure, communications and operations and maintenance do not distinguish one AHS component from the other.

5. FINDINGS

- It is possible to develop a process to identify AHS concepts.

- AHS goals and subgoals can be appropriately structured.

- 37 AHS concepts are defined in this research. This is not a complete and definitive set.

Title Platoon Collision Dynamics and Emergency Maneuvering III: Platoon Collision Models and Simulations

Date February, 1994

Authors Benson H. Tongue and Yean-Tzong Yang

Organization California PATH

1. SYSTEM CONCEPTS

Functional Performance

Velocity of 26.8 m/s at an intra-platoon spacing of 1 m.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The report documents the development of a platoon collision model which can be used to study platoon collision dynamics under emergency situations. The purpose of the project is to examine the behavior of a nonlinear platoon during non-nominal operations, to examine the platoon's nonlinear responses, and to investigate ways to mitigate any adverse effects due to non-nominal behavior. The effect of uncertainty in the system's response time, the effect of platoon size and the effect of the deceleration rate of the lead vehicle are investigated.

3. METHODOLOGY

A vehicle model, based on the previous year's results is modified by implementing a bumper model. A concept of back control has been introduced and the controller based this idea is compared to one having no knowledge of following vehicles' states. Two different cases are considered for each basic approach: inclusion or non-inclusion of lead vehicle information. Thus, a total of four platoons are examined.

4. ASSUMPTIONS

The power systems are assumed to exhibit response delay and saturation for both throttle and response systems. It is assumed that initial velocity for all vehicles is 26.8 m/s and the initial spacing is 1 m.

5. RESULTS

- The current simplified dynamic platoon model can be used successfully in the analysis of platoon collision dynamics.

- The vehicle behavior within a platoon depends strongly on the control algorithm.

- Unmodeled uncertainties can cause unpredictable deviations.

Title A Probabilistic Model and a Software Tool for AVCS/ Longitudinal Collision/Safety Analysis.

Date June, 1993.

Authors H.-S. Jacob Tsao and Randolph W. Hall.

Organization California PATH

1. SYSTEM CONCEPTS

Functional Performance

Parametric analysis for a range of failure rates, decelerations during failures, and vehicle headways. Allows for both platooning and non-platooning.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

To compare the safety consequences associated with the platooning and "free-agent" following rules.

3. METHODOLOGY

This paper develops a probabilistic model and a software tool for analyzing longitudinal safety/collision between two automated vehicles. The input parameters are the gap length between the two vehicles, the common speed prior to failure, the reaction delay of the following vehicle and a bivariate joint distribution of the deceleration rates of the to vehicles. The output includes the probability of a collision and also the probability distribution of the relative speed at collision time.

The principle of maximum entropy is used to derive a discrete bivariate distribution that satisfies user-specified marginal distributions, marginal standard deviations and coefficients of variation. A two-dimensional coordinate system is employed to represent the position of the two vehicle as a function of time. The computer tool developed has the following three modules: a MAXENT problem generator, a MAXENT solver and a collision probability and speed solver.

4. ASSUMPTIONS

Actual deceleration rate of the trailing vehicle is constant but random due to mechanical limitations. Further assumptions of the model include (1) the two vehicles are moving on a straight lane at common speed prior to failure (2) the failed vehicle decelerates at a constant but random rate (3) the following vehicle also decelerates at a constant but random rate after a reaction delay if it has not already collide with the failed vehicle and (4) the two rates are possibly correlated. In addition, for the purposes of comparing the platooning and free-agent rule, certain specific assumptions are made.

5. FINDINGS

- A vehicle failure would cause far more initial collisions under platooning. If a small fraction of relative low-speed collisions lead to major collisions, the platooning rule would be less safe.

- The free-agent rule, if provided with the potential technology of fast and accurate emergency deceleration, will avoid collisions while providing a capacity comparable to platooning.

- While the developed model is highly versatile and is applicable in a variety of analyses, further research is needed to extend the model and software to accommodate multiple collisions and curve of speed after deceleration.

Title Capacity of Automated Highway Systems: Effect of Platooning and Barriers

Date February, 1994

Authors H.-S.J.Tsao, R.W.Hall and B.Hongola

Organization: California PATH

1. SYSTEM CONCEPTS

Distribution of Intelligence (vehicle/roadside)

An AHS consists of two major components: vehicle/highway automation technology and highway operating strategy. A major design issue is the degree of cooperation among vehicles in order to facilitate lane changes. The roadside control system may manage gaps by moving vehicles.

Roadway Infrastructure

A major configuration option is the erection of lane barriers and "gates" for lane changes.

Functional Performance

The sustainable throughput of an AHS hinges on its configuration and operation. The degree of segregation is an important design decision. Vehicle uniformity makes control of automated vehicles simpler and safer. A range of lane throughputs (500-8000/hour) are analyzed, under platooning and non-platooning conditions, with varying exit rates.

Humans vs. Machines (roles and tasks)

All vehicles are equipped with automation equipment and they access the automated lane from the transition lane. The switch to automation takes place on the transition lane. Similarly, they switch back to the manual driving mode in the transition lane.

Communication Systems	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

The effect of the lane-flow rule, platooning or free-agent, as well as the lane barriers on highway capacity. The objective is to maximize the AHS flow subject to the constraint that all or nearly all of the users exit the AHS at their desired exits.

3. METHODOLOGY

The capacity estimation problem is tackled using two parallel but coordinated efforts: analytical modeling and computer simulation. SmartPath has been modified to study the effects of platooning and lane barriers on AHS capacity. Simulation focuses on a segregated AHS that has one automated lane and one transition lane. Several lane-change models have been developed for AHS scenarios without lane barriers and without lane-change cooperation among vehicles. For all the models, an axiomatic approach has been adopted. The models have been classified into two sections, one for the free-agent rule and one for platooning. These have been discussed in detail in the report.

Due to the complexity of analytical modeling, the effects of lane barriers on AHS capacity are studied only through simulation. Major modifications were made to SmartPath to study the impacts of different combinations of lane-flow rules and barrier options. The five focal design options have led to six sets of simulation experiments.

4. ASSUMPTIONS

Since this paper concentrates on operating strategy it assumes the feasibility of the automation technology that supports the AHS. Driver/public acceptability of the operating strategies are also assumed. Only one type of vehicle is assumed to be accommodated on the AHS. It is assumed that there is no cooperation among vehicles for lane changes.

5. FINDINGS

- In many test cases, the exit success rates are well below 100%. These rates are particularly low in cases where the flow rate and the exit percentage are both high.

- Free-agent cases tend to have a much lower success rate for exiting than platooning cases, for a given lane throughput. In platooning, the bottleneck flow occurs earlier in the segment d ue to platooning splits, and the flow subsequently increases.

- The presence of barriers results in greater congestion. Lane change maneuvers take longer in the automated lane.

- When the safety distance is larger, the lane changes are more restrictive and the bottleneck flows are lower.

- Neither the analytical nor the simulation models adequately represent a future AHS. More sophisticated strategies and models are required.

- The analytical models and the simulation results indicate a trad e-off between the longitudinal and the lateral capacities of an AHS.

- More study is suggested to accurately define the concepts and measures of AHS capacity.

Title AHS Evolution

Date 1994

Authors Center for Advanced Transportation,
University of Southern California

Organization Raytheon

1. SYSTEM CONCEPTS

Deployment Concept

Six levels of automation are defined:

0: Today's freeways with HOV lanes and some traffic warning lights.
1: Dedicated lane for vehicles with AICC, and the roadway commands the speed and gaps.
2: Steering assist and vehicle-vehicle communication.
3: Hands-off steering in a single lane and longitudinal collision avoidance.
4: Vehicles change lanes with automatic lateral collision avoidance.
5: Fully automated highway.

Factors below are discussed within deployment concept.

Distribution of Intelligence (vehicle/roadside)
Communication System
Type of Information Communicated
Sensors
Actuators
Changes to Roadway Infrastructure
Functional Performance
Humans vs. Machines (roles and tasks)

2. IMPACTS STUDIED IN RESEARCH

This document is concerned with the reliability, performance requirements and evolutionary path for the roadway, vehicle and driver at each level of automation.

3. METHODOLOGY

This report describe an evolutionary path that highlights the process of automation and looks at the issues and risks at each stage. Each level is described in terms of the roadway, the driver and the vehicle. Each level, in turn, raises new issues and risks. The reliability, performance requirements and evolutionary path for the roadway, vehicle and driver are studied at each level.

4. ASSUMPTIONS

Cars are treated as "packets of data" and routed along the highway. The most advanced scenarios treats vehicles as dumb entities that follow instructions given by the roadway. Instrumentation progressively shifts from vehicles to roadway.

5. FINDINGS

- Automated systems need to be more reliable than the current system that they replace.

- Steering assist stabilizes the vehicle by compensating for high frequency disturbances in the roadway.

- Sensors are expected to improve safety in general.

Title A Hypothesized Evolution of an Automated Highway System

Date November 26, 1993

Author Jerry D. Ward

Organization Rockwell International

1. SYSTEM CONCEPTS

Distribution of Intelligence (vehicle/roadside)

No data inputs from the road in most cases.

Communication System

A self-test and diagnostic system known as the "Integrity Verification subsystem;" same-lane vehicle-vehicle communication for platooning required.

Type of Information Communicated

Information relevant to spontaneous platooning decisions.

Sensors

On-board sensors to accurately determine vehicle position with respect to the roadway markings, a radar to calculate the range, an accelerometer to deduce road condition, machine-vision sensors, redundant sensors for greater reliability, and visible/RF reflectors.

Actuators

Reliable, fast and accurate braking (electronic) control actuators for the autobrake function, a sensitively modulated throttle control, better vernier control

Roadway Infrastructure

No major changes to roadway infrastructure in the foreseeable future, as AHS-ready vehicles are assumed to be operable on existing roadways in a mixed environment. Simple marks will be necessary to permit vehicle orientation.

Deployment Concept

A technically sensible evolution, with each step building upon previous steps and spread over several years. At each stage of deployment, there should be reasonable correlation in time and degree between costs and benefits: i) Automatic Emergency Braking, ii) Automatic Gap Holding, iii) Automatic Lane Holding, iv) Automatic platooning and deplatooning, v) Automatic Lane Change, vi) Extension to surface streets, vii) Further evolution which is difficult to envision at this time.

Functional Performance

Braking reaction times reduced to about .1 or .2 seconds. Maximum vehicle speed of 88 kph (for 0.4g roads) and 120 kph (for 0.8g surfaces), assuming a sensor range of 76 meters.

Humans vs. Machines (roles and tasks)

Vehicle engagement and disengagement at volition of driver.

2. IMPACTS STUDIED IN RESEARCH

The scope of potential usefulness of various functions is briefly addressed; of some concern is the effect on congestion levels.

3. METHODOLOGY

The first step involves hypothesizing what is believed to be a sensible technical evolution of an AHS using the author's best judgment and knowledge from already available analyses. A sequence of deployment steps is also defined. No detailed analysis is carried out; it is left to a later stage subject to promising results here.

4. ASSUMPTIONS

- Automated vehicles are capable of safely operatin g in mixed traffic with unequipped, manually operated vehicles.

- A deceleration of 0.8g to 1.0g.

- Incremental costs of autogap are expected to be small.

- The first production model of an AICC is assumed to be $10,000, decreasing thereafter on a 90% learning curve.

- The first model of an AICC is assumed to cost $7500, decreasing to $827 after 2,000,000 units.

- Platooning may lead to a slight net reduction in safety while providing no relief from existing driver chores.

5. FINDINGS

- Automatic braking will improve safety beyond human capability.

- Autogaps offer "relief" to the driver.

- Reduction in congestion due to platooning.
- Platooning on surface streets requires more investigation.

Title Drag Measurements on a Platoon of Vehicles

Date February, 1994

Authors Michael Zabat, Stefano Frascaroli and Fredrick Browand

Organization California PATH

1. SYSTEM CONCEPTS

Functional Performance

Assumes close formation platoons.

Distribution of Intelligence (vehicle/roadside)	Not Discussed
Communication System	Not Discussed
Type of Information Communicated	Not Discussed
Sensors	Not Discussed
Actuators	Not Discussed
Changes to Roadway Infrastructure	Not Discussed
Deployment Concept	Not Discussed
Humans vs. Machines (roles and tasks)	Not Discussed

2. IMPACTS STUDIED IN RESEARCH

This report details the design and implementation of wind tunnel tests to evaluate the aerodynamic performance of individual members of 2, 3 and 4-vehicle platoons. The purpose of the tests described here is to quantify the behavior of vehicle drag, or drag coefficient, as a function of vehicle spacing.

3. METHODOLOGY

One-eighth scale models of the 1991 GM Lumina van are used as the prototype vehicle. The measurement of drag, side force and yaw movement is described. Models are mounted above a porous plane surface designed to control the surface boundary layer thickness.

4. ASSUMPTIONS

Close formation platooning is assumed.

5. FINDINGS

Results show a reduction of almost 40% in average drag for a 4-vehicle platoon at 1/2-car length spacing. Based on the data presented, some conclusions are drawn as to the expected drag reduction for a platoon of any size. The low average drag coefficients for platoon operation translate to increased fuel savings and less pollution per km traveled.

CHAPTER 2: INTERIM RESULTS FROM PRECURSOR SYSTEM ANALYSIS WORKSHOP, APRIL, 1994

The following results are based on selected presentations from the Precursor System Analysis Workshop, held in Washington, D.C., in April 1994. While these results are preliminary, they are provided in order to give a sense of the latest research on AHS benefits and impacts. Results are sequenced alphabetically by author. For each presentation, information is provided on: (1) impacts studied and methodology, (2) system concept, and (3) findings.

<u>Title</u> Influence of Urban/Rural Characteristics on AHS

<u>Author</u> Jeff Benson

<u>Organization</u> Battelle/BRW

1. IMPACTS STUDIED AND METHODOLOGY

The key work tasks include a literature search, forming an expert panel, documenting technical and operational characteristics/issues and identifying opportunities and risks. Technical issues include geometric design characteristics and vehicle characteristics. Operational issues may be identified according to trip (speed, density, headway etc.), accident (rates, types, severity and effects of traffic mgt.) and traffic flow characteristics (length, purpose and trip time). Opportunities and risks are identified individually in each area (urban, rural and fringe).

2. SYSTEM CONCEPT

Geometric characteristics are categorized according to interchange configuration, number of lanes, lane width, interchange spacing and curvature, while vehicle characteristics are classified by physical requirements.

3. FINDINGS

Various statistics are provided on the following:

- Minnesota freeway accident rates 1990-92: rural, urban and fringe.
- Freeway accident severity, Minnesota 1990-92: rural, urban and fringe.
- Types of freeway accidents, Minnesota 1990-92: rural, urban and fringe.
- Severity of accidents susceptible to correction by freeway area type.
- Potential annual accident reduction figures.

Title Potential AHS Roadway Characteristics and Configurations

Author Dave Bruggerman

Organization Battelle/BRW

1. IMPACTS STUDIED AND METHODOLOGY

The purpose of this analysis is to identify the issues and risks associated with the deployment of an AHS from the perspective of the physical roadway and its associated characteristics. The analysis approach includes: identification of issues, a generic analysis, State DOT input, specific site analysis and evolution strategies.

2. SYSTEM CONCEPT

With respect to the urban/fringe environment, the various options include a positive barrier between AHS and non-AHS lanes, two AHS lanes per direction and exclusive entry/exit facilities.

If a 4-lane mixed flow scenario is considered in the rural environment, then an option would be an exclusive AHS lane to the left of non-AHS lanes.

3. FINDINGS

Factors affecting AHS lane width include design vehicle width, accuracy of lateral control, driver comfort, travel speed and adjacent features. Also provided is a comparison of the level of benefits of shoulders in AHS and non-AHS scenarios. Different situations are discussed with various options in each case.

<u>Title</u> Commercial and Transit

<u>Author</u> Margin C. Gersten

<u>Organization</u> Calspan/Parsons Brinckerhoff

1. IMPACTS STUDIED AND RESEARCH

This report studies the usage of interstate highways and toll roads by heavy trucks. It examines the relevance of truck size and weight issues to AHS, size and weight restrictions and cost implications. The question of whether AHS should be designed exclusively for passenger vehicles, buses and single unit trucks is raised.

2. SYSTEM CONCEPT

Truck properties that are affected by weight and/or configuration include: Rollover, Hydroplaning, Rearward amplification, Braking, Steering sensitivity, High speed offtracking. Pavement design and life expectancy is influenced by the following truck characteristics: Tire pressure, Number of tires, Suspension system, Axle spacing. Heavy vehicles can cause overstress and fatigue to bridges. Multiple truck convoys on exclusive AHS pavement and bridges will require extra structural sections. Characteristics of traffic operations are affected by the weight and configuration of trucks: Speed on upgrades, Freeway merging and weaving, Downhill operations, Traction, Longitudinal barriers.

3. FINDINGS

Statistics are provided for heavy truck usage of both urban and rural sections interstate highways and toll roads in the states of New York, New Jersey and California.

Further findings may be summarized as follows:

- 40% of truck accidents are attributed to driver.
- Speeding, tailgating, improper turning and careles s lane changing by the driver is a major cause of accidents.
- Fatigue is a primary factor in truck accidents.
- 10% of all heavy truck accidents involve mechanical defects.
- Defective braking systems contribute to 33% of all mechanical faults.
- Disparity between truck and passenger vehicle braking distances contributes to accidents.
- ABS and compatible truck and trailer braking systems are needed.
- The motor carrier needs to conduct safety training and maintenance programs and adjust delivery schedules and driver hours to help prevent truck accidents.

Title Early Results in AHS Throughput Performance Analysis

Author Robert L. Gordon

Organization Dunn Engineering Associates

1. IMPACTS STUDIED AND METHODOLOGY

The objective of this research is to conduct an analysis of throughput in an AHS system. A section of the Long Island Expressway was used as part of this study.

2. SYSTEM CONCEPT

System throughput is defined by the following:

- Performance parameters of the AHS (e.g. speed vs. volume).
- AHS entry and exit locations.
- Transportation demand characteristics.
- Constraints imposed by non-AHS roadways.

3. FINDINGS

The major results to date may be summarized as follows:

- An AHS system supports both the AHS roadway and the supporting non-AHS roadways.
- Total system throughput depends on both AHS capacity as well as the capability of supporting non-AHS highways.
- Preliminary results show that AHS has the potential to reduce the Long Island Express way travel time by approximately one half.
- AHS in other locations will provide benefit improvements in both capacity and travel time.

Title Types of Institutional/Society Issues

Author Alan Lubiner

Organization Calspan/Parsons Brinckerhoff

1. IMPACTS STUDIED AND METHODOLOGY

The purpose of this study is to provide a comprehensive catalogue of institutional and societal issues/risks, document the relevance of each issue by RSC, provide a funding an financial analysis and focus on key issues and risks requiring additional study. Assumptions are made with regard to the extent to which previous comparable technologies can be applied to AHS deployment, the evolution of AHS from IVHS research and design and the importance of institutional/societal issues.

2. SYSTEM CONCEPT

AHS is likely to evolve from IVHS research and design. A centralized power supply is likely to reduce emissions. Existing RSCs may require infrastructure changes because of noise and visual impact concerns.

3. FINDINGS

Major findings are listed for each of the categories mentioned above and are described in detail along with the finding mechanisms. Among the important issues/results to date are:

- Most of the "difficult" institutional and societal issues are being addressed by the current IVHS program.
- AVCS and AHS RSCs pose new questions about liability laws.
- Public acceptance and education issues remain.

Title Lateral & Longitudinal Control Analysis: Results/Issues of Headway Maintenance

Author Lyndon I. Ma

Organization Rockwell

1. IMPACTS STUDIED AND METHODOLOGY

The Rockwell approach to lateral/longitudinal control involves performing AHS system operational analyses in terms of safety and capacity in the five areas of headway maintenance, lane change maneuver, platoon formation, obstacle avoidance maneuver and traffic stream stability. It also involves identifying issues and risks. The major assumption in safety formulation is that vehicles brake along a longitudinal axis.

2. SYSTEM CONCEPT

The parameters that may affect safety are vehicle states, condition of the road surface, tires, vehicle mass, capacity, platoons etc. Establishing a safe gap between vehicles adaptively in real time and whether safety should be established based on worst case or a statistical consideration of each parameter or a combination are some of the issues involved. Independent sensing is a major assumption in headway maintenance, while ride comfort, minimum bandwidth of headway maintenance, maximum tolerable gap variation and maximum tolerable impact energy are the issues involved.

3. FINDINGS

Interim results are provided in the area of headway maintenance. Platoons, their capacity, functioning and other parameters are also examined in detail. Data pertaining to headway are also provided.

Title Comparable Systems Analysis: HOV Lanes and Ramp Metering

Author Doug Munke

Organization Calspan

1. IMPACTS STUDIED AND METHODOLOGY

The research approach consists of conducting high-level studies of several comparable systems - highway-based, vehicle-based, other transportation systems as well as non-transportation-based systems- a review of literature and application of team expertise. The interim results briefed in this session cover HOV lanes and ramp metering.

2. SYSTEM CONCEPT

It is assumed that HOVs and ramp metering are highly comparable to AHS because they are implemented on current highways with current driver populations and involve novel approaches to freeway operation. Objectives in both cases are to reduce congestion and improve flow. Issues of public acceptance are central and success is impacted by infrastructure design issues.

3. FINDINGS

The various HOV design issues and their relevance to AHS are tabulated. A comparison is made of people moving potential under existing facilities and AHS under different speeds. On a similar level, ramp metering design issues and their relevance to AHS are considered. A list of benefits is also provided: existing guidelines for ramp metering and HOV deployment have direct implications for AHS, public acceptance will be enhanced if benefits are made obvious and AHS can reduce congestion if combined with transit and HOV treatments. However, details should not be overlooked.

Title Human Factors Design of Automated Highway Systems

Authors Robert A. North

Organization Honeywell

1. IMPACTS STUDIED AND METHODOLOGY

This study provides human factors analytic support during the conceptual stages of AHS development to affect the design and implementation of the 1997 demonstration and provide the foundation for future, advanced development of automated highway systems. Stage I consists of the following tasks:

- Objectives and performance requirements (7 scenarios defined).
- Definition of elemental functions (completed).
- Function allocation (draft working paper submitted).
- Driver performance requirements (3 scenarios analyzed).
- Preliminary handbook (12 chapters being compiled).
- Research issue and experimental workplans (1-3 submitted, 4-7 being finalized).
- Conduct research (3 experiments conducted).

Stage II uses the results of Stage I as input for the following tasks:

- Driver task analysis.
- Experimental workplans.
- Conduct research on workplans.
- Human factors guidelines and research issues.
- Second generation handbook.
- Stage II report.

2. SYSTEM CONCEPT

The following scenarios are analyzed :

- Free agent/self-contained
- Segregated highway/individual vehicles
- Barriers/grouped vehicles

3. FINDINGS

The results obtained to date are summarized below.

Problem Areas

- Destination and route selection may cause a significant workload problem while driving manually.
- Notification of inspection failure for faulty and non-equipped vehicles.
- Driver as back-up to the AHS equipment may not be effective.

- Partial automation scenarios (like free-agent/self-contained) may cause drivers to place unwarranted complacency on them.

Selected Lessons Learned from Comparable Systems Analysis

- Nuisance messages can increase workload unnecessarily.
- Forcible stoppage of vehicle if driver disregards an alert.
- Preventing drivers from steering under automated control.
- Study whether movement of steering, accelerator and brake during automated control make any difference in driver performance.
- Inhibit warning systems that may be prone to false alarm

Preliminary Findings

- Driver route selection may be problematic.
- Mechanism needed to suppress low priority communications.
- Human driver may be a poor back-up for steering failures.
- Driver back-up for speed and headway control possible

Title AHS Accident Analyses

Authors Linda O. Parada and Mary M. Lloyd

Organization Calspan

1. IMPACTS STUDIED AND METHODOLOGY

The objectives of this study are fault hazard analysis, support analysis for other tasks' safety issues and development of a safety data resource for all tasks. The following data sources were used for this study:

GES : Nationally representative police reported data on fatalities, injuries and major incidents of property damage.

FARS : Police reported fatal traffic crashes, accidents within 30 days of death of occupant or non-motorist and data from existing state documents.

CDS : Clinical Analysis, police reported crashes, probability samples, incidents of personal injury or property damage and interviews.

2. SYSTEM CONCEPT

In the analysis of rear-end crashes, the scenario involves a manual vehicle (reaction time of 1.75 sec.) trailing an automated vehicle (reaction time of 0.3 sec.) that brakes suddenly. The applicable RSCs are:

- Initial AHS - automated and manual vehicles in the same lane.
- Transition lane for RSCs with separate AHS lanes.
- Dedicated AHS with malfunction.

The analysis of barrier related crashes has the following RSCs applicable:

- Conventional highways with separate AHS lanes.
- Dedicated AHS with barriers.

3. FINDINGS

The following "relevant" types of conventional highway accidents may be applicable to the AHS scenario: Rear-end, Barrier related crashes, Run off road, Lane change/merge, Mixed vehicle-type crashes, Object/animal in roadway, Driver impairments. Statistics are provided on the following:
General Accident Characteristics: Accident type, vehicle damage severity, maximum injury severity and number injured. Rear End Accident Characteristics: Location, lighting condition, weather condition, roadway surface condition, vehicle damage severity, maximum injury severity, number injured and driver violations. Barrier Related Accident Characteristics: Location, lighting condition, weather condition, roadway surface condition, vehicle damage severity, maximum injury severity, number injured and driver violations.

Title AHS Fault Trees and Malfunctions

Author P.A. Reynolds

Organization Calspan

1. IMPACTS STUDIED AND METHODOLOGY

The objective of this research is to expose issues arising from various AHS functional degradations. The major initial issues are i) Faults that cause an individual to stop, slow, partially/totally lose AHS functionality and ii) Right of way impairment due to accidents in adjacent lanes, objects in the lane(s) and inadvertent/deliberate manual encroachment.

2. SYSTEM CONCEPT

The AHS functions are check-in, mode selection, access, gap regularization, lane change, malfunction management in lane, breakdown lane select, check-out and egress. The following are the operational components of an AHS: Vehicle, Roadway, Environment, Driver, Passengers/Goods. Details of operational components of the vehicle and vehicle subsystems are provided.

3. FINDINGS

A comparison is made between the breakdown frequencies of the Toronto 401 and the Bay Bridge. Percentages are provided for each of the following breakdown scenarios: mechanical/other/abandoned, out of gas, flat tire, accident and overheating (assumed). Further interim results may be summarized as follows:

- A vehicle-based system as a back-up with data link enhancements can be used to minimize the impact of data link failure.

- The driver is most effective in malfunction management as the on-call supervisor of an automatic malfunction management system.

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Title Effects of AHS Surrounding Non-AHS Roadways

Author Randy Schulze

Organization Delco/DMJM

1. IMPACTS STUDIED AND METHODOLOGY

The purpose of this study is to determine the impacts of AHS on non-AHS roadways. Interim results were obtained using the following study approach: 3 RSCs, 3 AHCs, urban and rural, commercial and transit, FREQ modeling of side by side scenarios, operational MOEs and operational model, no demand modeling.

2. SYSTEM CONCEPT

The RSCs are infrastructure-centered platoon control, vehicle centered platoon control and space-time slot control. AHCs include a new AHS on a new alignment, a new AHS in existing freeway R-O-W and conversion of existing HOV or mixed freeway to AHS.

Hypothetical urban and rural freeways are analyzed. The check-in parameters are dedicated or non-dedicated entry, check-in length, time, stopping and AHS mainline speed. The check-in lengths are deceleration, transition, queue length, check-in facility length, pass-fail maneuver and acceleration lengths.

3. FINDINGS

The interim results are AHCs, MOEs, check-in parameters and mainline differential effects. The issues encountered while determining check-in length are entry-exit size, AHS capacity and the necessity to use caution in modeling results. Measures of operational effectiveness of AHS are provided, assuming a 25% AHS market penetration, for speed, vehicle hours, fuel consumption, and air quality.

<u>Title</u> Alternate Approaches for AHS Entry/Exit

<u>Author</u> William R. Youngblood

<u>Organization</u> Raytheon/Georgia Tech

1. IMPACTS STUDIED AND METHODOLOGY

Issues addressed include evolutionary RSCs, entry/exit configuration types, entry/exit functional flow, entry/exit evaluation criteria and entry/exit configurations. The research thrust is on a whole system view, evolutionary deployment of AHS functions and on roadway/infrastructure.

The methodology involves the following steps: define evolutionary RSCs (ERSCs), identify entry/exit criteria, development of AHS travel functional flows and entry/exit configurations, mapping/adapting additional flows, address design issues, critique configurations using evaluation criteria and refine the configurations.

2. SYSTEM CONCEPT

The entry/exit configuration types addressed are freeway-AHS (with 4 variants), surface-AHS (2), AHS-AHS (2) and safety lane-AHS. Under entry/exit functional flow, potential entry/exit problems for various aspects of nominal travel (e.g., entry, check-in, transition, merge, exit etc.) are identified and tabulated. Entry/exit evaluation criteria include functional effectiveness, safety, operational access, cost and evolutionary compatibility.

3. FINDINGS

Five different ERSCs (each with two variants) are evaluated for different vehicle operations and roadway features.