Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Performance Measures Analysis – Task Q

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-96-055
February 1996

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

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-96-055		

4. Title and Subtitle	5. Report Date
Precursor Systems Analyses Of Automated Highway Systems: Performance Measures Analysis-Task Q	February 1996
	6. Performing Organization Code
7. Author(s) Calspan and Dunn Engineering	8. Performing Organization Report No.
9. Performing Organization Name and Address Calspan Corporation Advanced Technology Center P.O. Box 400 Buffalo, New York 14225	10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-93-C-00192
12. Sponsoring Agency Name and Address Federal Highway Administration Turner-Fairbank Highway Research Center 6300 Georgetown Pike, McLean, Virginia 22101	13. Type of Report and Period Covered Final Report 9/93-11/94 Resource Materials 14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative (COTR) – J. Richard Bishop

16. Abstract

This report summarizes an analysis to identify performance measures to be used in comparing alternative Automated Highway Systems (AHS) concepts.

This document type is resource materials.

17. Key Words	18. Distribution Statement
Automated Highway Systems Intelligent Vehicle Highway System Intelligent Transportation Systems	No restrictions. This document is available to the public through the National Technical Information Services, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	402	

Form DOT F 1700.7 (8-72)Reproduction of completed page authorized

(PF V2.1, 6/30/92)

Table of Contents

List of Tables

List of Figures

CALSPAN PRECURSOR SYSTEMS ANALYSIS

TASK Q - PERFORMANCE MEASURES ANALYSIS

1.0 INTRODUCTION

As part of Calspan's Precursor Systems Analysis program, we started an analysis effort to identify performance measures to be used in comparing alternative AHS concepts. This report summarizes our work in this area.*

The evaluation measures of effectiveness (MOEs) for the AHS system should be defined based on past experience and research. Specifically, they should meet the following requirements:

- MOEs that are applied to current highways and transportation systems should be defined for AHS wherever applicable. By applying established MOEs it will be possible to compare measures of AHS performance to data already available from conventional systems (e.g., conventional highways, HOVs). Also, by using established MOEs, the interpretability and sensitivity of the measures will be known, and communication of the resulting data within the transportation community will be facilitated. Proven approaches to data collection are also more available when using standard techniques.
- MOEs applied to assess AHS unique features should be developed oil basis q[the PSA of AHS research. These MOEs should be developed to assess the degree to which an AHS design meets AHS objectives and desired characteristics. By building upon existing AHS related research foundation (e.g., the PSA of AHS studies), MOEs can be focused on the most important issues related to AHS performance.

The focus of this report is on development of MOEs of the second category, since a large portion of the PSA of AHS effort dealt with AHS unique issues and concerns. The application of more standard highway and transportation MOEs needs to be added using the process and structure described.

The PSA of AHS research results represent one year of focused technical effort accomplished by several study teams. AHS design issues and performance requirements are documented within many volumes of reports and are summarized within an issues database. The ambitious schedule for the NAHSC effort requires rapid assimilation of this work. Further, these results represent important facets of the evaluation process that should not be overlooked.

---

*The work in the *main* body of this report was performed by Calspan staff. A separate. parallel **effort** was **performed** by Dunn Engineering **Associates** and is presented as Appendix A.

Our approach on this task is to provide summaries of major AHS design and evaluation issues mapped to the design and evaluation structure being used by the NAHSC'. It provides: (1) a high level summary of main results of Calspan's PSA of MIS effort within the structure of the NAHSC requirements document for a small subset of the PSA analysis; and (2) a reference to Calspan's PSA of AHS final report where more detailed information can be found. These results are structured and presented for use in defining MIS performance measurement requirements and the supporting MOEs.

It Is important to note that the final set of MOEs will need to be tailored to the specific concepts being evaluated to some extent. For example, MOEs associated with AHS entry will be different when applied to an Ii concept (mixed traffic) versus an 13 concept (dedicated AHS). The examples in this document have not yet attempted to deal with the specific needs of various AHS concept types.

2.0 METHODOLOGY

The methodology applied in the development of this document involved a three-step process. First, the preliminary AHS Description Document objectives and characteristics were matrixed to AHS performance objective categories. Second, the evaluation oriented PSA of AHS issues were summarized within this structure and references to the main report were added. Third, MOEs describing actual metrics and specific questions to be answered are defined based on the issues identified in step two.

The NAHSC requirements outline that formed the starting point for this analysis is shown in Table 1 below. Two of the more important design characteristics, affordability and evolvability (also referred to as deployability in the MIS Description Document), were added to the supplied list of design objectives after consideration of their overall importance. These are important enough to be treated as system level objectives for the purposes of our study. Table 2 shows an example portion of the matrix of design characteristics with respect to the AHS objectives.

'We were provided NAH SC preliminary system definition documents in December. 1994 from Parsons Brinckeroff.

Table 1. NAHSC Provided Outline of AHS Requirements

SECTION	DESCRIPTION
3.0	**REQUIREMENTS**
3.1	**System Description**
3.2	**Performance Objectives**
3.2.1	Safety
3.2.2	Throughput
3.2.3	Inclement Weather Operations
3.2.4	Enhanced Mobility
3.2.5	Improved User Comfort & Convenience
3.2.6	Reduced Fuel Consumption & Emissions
3.3	**System Characteristics**
3.3.1	Affordability
3.3.2	User Desirability
3.3.3	Effect on Surrounding Non-AHS Roadways
3.3.4	Vehicle Instrumentation
3.3.5	System Technology
3.3.6	Evolvability
3.3.7	Vehicle Type
3.3.8	Roadway Type
3.3.9	Intermodality
3.3.10	Environmental Impacts
3.4	**Operational Requirements**
3.4.1	Check-In
3.4.1.1	Pre Check-In Inspections & Test
3.4.1.1.1	Vehicle Identification
3.4.1.1.2	Destination Information
3.4.1.1.3	Periodic Certifications
3.4.1.1.4	Check Vehicle Subsystems
3.4.1.1.4.1	Initial Self Test
3.4.1.1.4.2	Continuous Built-In Test
3.4.1.1.4.3	Roadside Non-Contact Testing
3.4.1.1.5	Special Equipment (Chains, Tires, etc.)
3.4.1.2	Verification of Operator License and Insurance
3.4.1.3	Verification of Vehicle Registration and Operating Certification

Table 1. NAHSC Provided Outline of AHS Requirements (continued)

SECTION	DESCRIPTION
3.4.1.4	Vehicle Systems Checks
3.4.1.4.1	Sensors
3.4.1.4.2	Actuators
3.4.1.4.3	Continuous Built-In Test
3.4.1.4.4	Roadside Non-Contact Testing
3.4.1.4.5	Inspection
3.4.1.5	Check-In Abort
3.4.1.6	Enforcement
3.4.1.7	Safe Sequence for Transfer from Manual to Automated Lanes
3.4.1.8	Vehicle Merging
3.4.1.9	Traffic Flow Control
3.4.1.10	Driver~Operator Interface
3.4.2	Roadway Operations
3.4.2.1	Automated Lane Keeping
3.4.2.2	Automated Headway Control
3.4.2.3	Coordinated Vehicle Maneuvering (Platooning)
3.4.2.4	Communications
3.4.2.5	Vehicle Diagnostics
3.4.2.6	Roadway Condition Determination
3.4.2.7	Trip Guidance & Control
3.4.2.9	Collision Avoidance
3.4.2.9.1	AHS Vehicles
3.4.2.9.2	Rogue Vehicles
3.4.2.9.3	Other Obstacles
3.4.2.9.3.1	Obstacles on Roadway
3.4.2.9.3.2	Animals Near Roadway
3.4.2.10	Vehicle Location
3.4.2.11	Human Factors
3.4.2.12	Driver/Operator Interface
3.4.3	Check-Out
3.4.3.1	Normal Check-Out
3.4.3.1.1	Driver Readiness
3.4.3.1.1.1	Alert Driver

Table 1. NAHSC Provided Outline of AHS Requirements (continued)

SECTION	DESCRIPTION
3.4.3.1.1.2	Verify Operator Competence
3.4.3.1.2	Vehicle Readiness
3.4.3.1.2.1	Verify Operation of Safety Critical Manual Vehicle Functions
3.4.3.1.2.2	Safe SOE for Transfer of Control from Automated to Manual
3.4.3.1.3	Check-Out Abort
3.4.3.2	Emergency Check-Out
3.4.3●3	Storage Area for Failed Vehicles
3.4.3.4	Driver(Operator Interface
3.4.4	Operations Management
3.4.4.1	Central Control Facility
3.4.4.2	Alternate Routing
3.4.4.3	Flow Management
3.4.4.4	Incident Management
3.4.4.4.1	Central Control Facility
3.4.4.4.2	Verification
3.4.4.4.3	Response
3.4.4.5	Modify System Operating Parameters
3.4.4.6	Emergency Service Management
3.4.4.7	Operator Interface
3.4.5	Malfunction Management
3.4.5.1	Subsystem Failure
3.4.5.2	Hazard Management
3.4.5.2.1	Man-Made Hazards
3.4.5.2.2	Natural Hazards
3.4.5.3	Emergency Abort
3.4.6	Information Management
3.4.7	Control Center Operations
3.4.8	Communications
3.5	**Interfaces**
3.5.J	Vehicle to Driver
3.5.2	Vehicle to Infrastructure
3.5.3	Driver to Infrastructure

Table 1. NAHSC Provided Outline of AHS Requirements (continued)

SECTION	DESCRIPTION
3.5.4	Vehicle to Other Vehicle
3.5.4.1	AHS Vehicle to AHS Vehicle
3~5.4.2	AHS Vehicle to Non-AHS Vehicle
3.6	**Deployment**
3.7	**Training**
3.7.1	Vehicle Operator
3.7.2	Control Center Operator
3.7.3	Vehicle Maintenance Personnel
3.11	**Reliability**
3.12	**Maintenance**
3.12.1	Preventative
3.12.2	Response
3.12.3	Record Keeping
3.14	**System Security**

Table 2. Example Portion of the Evaluation Analysis Matrix Illustrating the Format Used

Oper. Req.	**Performance Objectives**							
Check-Out	**Safety**	**Through -put**	**All Weather**	**Enhanced Mobility**	**User Comfort**	**Fuel & Emissions**	**Afford-ability**	**Evolva bilitv**
Normal Check-Out								
Driver alertness								
Driver competence								
Vehicle readiness								
Check-out abort								
Emergency Check-Out								
Storage Area for Failed Vehicles								
D river/Operator Interface								

It is recognized that the sensitivity of a given performance measure to the various design characteristics is not equal. A scale for indicating the weighting among performance objectives was created. This scale is shown in Table 3. The scale indicates the relative impact of each design category on the respective performance objectives.

Table 3. Interpretation of Evaluation Sensitivity Scorcs

Scale Value	Interpretation
blank	No impact, the evaluation category is not sensitive to this aspect of design
I	Minor impact, the evaluation category is only slightly sensitive to this aspect of design
2	(Between minor and moderate impact)
3	Moderate impact the evaluation category is sensitive to this aspect of design
4	*(Between* moderate and strong impact)
5	Strong impact, the evaluation category is extremely sensitive to this aspect of design

The second part of the methodology is populating the table with design issue summaries. Many of these issues are discussed in detail in Calspan's PSA of MIS final report and are included in the issues database. Specific references to the PSA of MIS final report sections are included in the table. The final version of the table will include issues *drawn* from all PSA of MIS reports as well as other relevant sources.

Finally, the design issues summarized in the table, and discussed in full in the PSA of MIS report, are used to define evaluation MOEs. This process is accomplished by interpreting and expanding the design issues in a way that allows their assessment within the context of evaluation. This involves determining how an evaluation MOE can be defined and applied to ensure that the particular design issue (or issues) are adequately dealt with within the AHS design.

As noted earlier, the preliminary draft of the AHS Description Document, dated 8 March 1995, differs somewhat from the outline and used to structure this work.

3.0 RESULTS

We are supplying results in the areas of check-out, check-in, malfunction management, training and reliability. These results are provided to illustrate the approach. Other areas can be analyzed using the methodology.

3.1 Check-Out

Candidate MIS check-out processes need to be evaluated to ensure that they provide adequate levels of safety, will not impede throughput, are acceptable to drivers (user comfort), are affordable, and are able to be implemented in an evolutionary fashion. The evaluation must ensure check-out adequacy with respect to each of these categories for both nominal and emergency check-out situations. Further, the implications of the check-out system on AHS infrastructure requirements must be assessed. Table 4 shows our estimate of the relative sensitivity of each check-out evaluation category to the major check-out design components.

Table 4. Relative Sensitivity of Check-Out Performance Objectives to Check-Out Operational Requirements

Oper. Req.	Performance Objectives							
Check-Out	**Safety**	**Through -put**	**All Weather**	**Enhanced Mobility**	**User Comfort**	**Fuel & Emissions**	**Afford-ability**	**Evolv-ability**
Normal Check-Out								
Driver alertness	5	2			2		1	2
Driver competence	3	2			2		1	2
Vehicle readiness	4						1	2
Check-out abort								
Emergency Check-Out	5				2			2
Storage Area for Failed Vehicles		2					4	.'
Driver/Operator Interface	5	3			-,			

* **A!!** items scoring a 2 or **greater** are discussed in Table **5 below.**

Table 5 summarizes evaluation-related issues identified during the PSA of AHS Study within the NAHSC requirements structure.

The next step in the methodology is to translate the AHS design issues described in Table 5 into requirements linked to specific MOEs. This can be accomplished by interpreting the details of the PSA of AHS reports and other relevant research and documents within an evaluation framework. This involves determining evaluation approaches and metrics for ensuring that the design issues are satisfied. A few examples will illustrate.

The first issue defined in Table 5 is that the check-out process should: (1) help restore alertness and (2) test for adequate alertness. Related issues state that the process should address all alertness-related aspects of driver behavior (stimuli detection, discrimination, recognition, and comprehension), and that the process should be related to the driving situation (e.g., not just ensure alertness, but alertness to the roadway etc.). From these issues, requirements and related

Table 5. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-Out

Oper. Req.	Performance Objectives				
Check-Out	**Safety**	**Throughput**	**User Comfort**	**Affordability**	**Evolvability**
Normal Check-Out Driver alertness *(Volume 4, Chapter 2, Section 1.2.3. Driver Readiness Issues, Section 3.2. Driver Readiness Issues)*	- The check-out process should: (1) help restore alertness and (2) test for adequate alertness - *The* check-out process must be appropriate for range of driver categories (e.g. elderly) - The process should addresses all alertness aspects of driver behavior - The process should be related to the driving situation (e.g., not just ensure alertness, but alertness to the roadway etc.) - The process for assuring driver readiness should build on the human factors research related to vigilance and information processing. - If check-out is failed there must be provisions for automatically parking the vehicle or sending the it to die next exit	- Check-out tests should be accomplished within tile check-out and transition process (and not constrain throughput) - Check-out process should be started early enough to allow for completion before transfer of control point - Allow time/space for re-test if check-out failed	- Check-out process should not be intrusive, difficult, and/or annoy in" - Check-out test (especially for periodic, ongoing tests rather than tests at exits) should be meaningful to the task of travel (e.g., system status, upcoming exits, etc.)		- adapt to ','evolving driver roles (especially role during AHS operation and malfunction management)
Normal Check-Out Driver competence (Volume 4, Chapter 2, Section 1.2.3, Driver Readiness Issues; Section 3.2, Driver Readiness Issues)	- The check-out process should address all important aspects of driver performance - The driver should be required to take control rather than be give control of die vehicle. - If check-out is failed there must be provisions for automatically parking the vehicle or sending it to the next exit	(same concerns as above)	(same concerns as above)		(same concerns as above)

Table 5. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-Out (continued)

Oper. Req.	Performance Objectives				
Check-Out	**Safety**	**Throughput**	**User Comfort**	**Affordabilitv**	**Evolvability**
Normal Check-Out Vehicle readiness (Volume 4, **Chapter** 2, Section **1.2.4,** Vehicle Readiness Issues; Section 3.3 Vehicle Check-Out **Issues)**	- All safety critical Systems not used during automated driving need to be verified **during** check-out. - Consider fail-safe **switch** interlock approaches for mechanical switching design. - Consider control response **testing** approach for **software** switching design. - If **check-out** is failed there must be provisions for automatically parking the vehicle or sending the it to **~e** next exit				- **Must be able** to **evolving AHS design and supporting technology**
Normal Check-Out Check-out abort ***(,E** specifically* ***addressed)***					
Emergency Check-Out (Volume 4, Chapter 2, Section 2.1.2 **Emergency Check-Out; 3.2 Driver Readiness Issues;** 3.2.3.1 Implication of Driver Role)	- If emergency **check-out** has a driver role, driver must remain alert **throughout trip** and this needs **to be periodically verified.** - **May need salient alarm for situations** requiring immediate human intervention.		- If periodic driver **alertness tests are required (e.g., the driver has role in malfunction management and/or** system monitoring) then the tests should be meaningful (e.g., associated with the trip)		- Check-out **should** be **able to** adapt to the **evolving AHS design mid associated driver role.**

Table 5. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-Out (continued)

Oper. Req.	Performance Objectives				
Check-Out	**Safety**	**Throughput**	**User Comfort**	**Affordability**	**Evolvability**
Storage Area for Failed Vehicles (Volume 4, Chapter 2, Section 3.4 Highway/AHS Design Issues)		- The storage area for failed vehicles must be sufficient to handle all failed vehicles.		- If failed vehicles are to be parked, adequate space must be provided, this will be a significant cost driver.	
Driver/Operator Interface (Volume 4, Chapter 2, Section 1.2.3 Driver Readiness Issues; 3.2 Driver Readiness Issues)	- The check-out driver interface will be a critical element for its success -- must be tested for usability - The check-out procedure should be obvious to use, and compatible with the driving tasks.	- The driver readiness test should be an integrated portion of the check-out process.	- Tests should he meaningful (e.g., associated with the task of traveling on the AHS), unintrusive, and should not be annoying.		

MOEs appropriate for assessing candidate check-out processes can be determined. Example MOEs that address these questions are shown in Table **6.**

These MOEs need to be expanded to include all relevant issues in Table 5. For **example** issues relating to throughput and consideration of requirements for re-test need to be added. By developing the AHS-unique evaluation factors based on MIS design requirements and drawing from existing relevant research, the resulting MOEs will be comprehensive and supported by the best available research base available Table 7 shows our estimate of the relative sensitivity of each check-in evaluation category to the major check-in design components.

3.2 Check-In

Check-in functions need to be closely evaluated for adequate safety. Vehicles with faulty components that pass the check-in inspection pose a threat to all MIS users. In addition to being a safety risk, vehicles with faulty or malfunctioning components risk a breakdown that could affect the throughput of the AHS lanes and cause an increase in driver travel time as well as stress level. Table 8 summarizes evaluation-related issues identified during the PSA of AHS Study within the NAHSC requirements structure.

Check-In is addressed in Calspan's Precursor System Analysis of Automated Highway systems report, Volume 4 (Check-In). A majority of the comments were derived from chapter 1.

Table 6. Example Requirement Matrix

Requirement Evaluation	Verification Approach	MOE	score*	Passed Yes	Passed No
Is the candidate check-out process designed and structured in a way that will help a driver who has not been attending to the driving task to become aware of the driving situation dynamics?	Test. Tests using representative subjects and realistic AHS use characteristics (e.g., trip duration) must be verified using a driving simulator.	Apply SAGAT (Situation Awareness Global Assessment Technique) test at point of control transfer			
Are all important components of driver alertness and performance included in tile check-out process (stimuli detection, discrimination, recognition)? Does the check-out process require the driver to attend to stimuli in the future view? Does it require demonstration of stimuli detection aid discrimination, recognition and comprehension, and correct decision and response?	Analysis. Review check-out procedure to ensure that all items are covered.	Relate subjective scale to score			
Does tile check-out evaluation require adequate demonstration of driver alertness before allowing the driver to take control? Has this been verified empirically for all potential driver populations? Is the test and associated criteria set to provide adequate differentiation without an unacceptable false alarm rate?	Test. Tests using representative subjects and realistic AHS use characteristics (e.g., trip duration) must be verified using a driving simulator.	Apply measures of driving performance (e.g., lane deviation, false alarm rate related to driving performance)			

Score: 1 = did not pass: 2=marginally passed: 3=clearly passed

Table 7. Relative Sensitivity of Check-In Performance Objective to Check-In Operational Requirements

Oper. Req.	Performance Objectives							
Check-In	Safety	Through -put	All Weather	Enhanced Mobility	User Comfort	Fuel & Emission	Afford-ability	Evolv-ability
Pre Check-In Inspection & Test								
Vehicle Identification		0						
Destination Information			3					
Periodic Certifications	3							
Check Vehicle Subsystems								
Initial Self Test	5							
Continuous Built-In Test	5	3						
Roadside Non-Contact Testing	5							
Verification of Vehicle Registration & Operating Certification	3							
Vehicle systems Checks								
Sensors and Control Systems	S							
Actuators	5							
Continuous Built-In Test	5							
Roadside Non-Contact Testing	5							
Inspection	3							
Check-In Abort	3	3						
Enforcement	3							
Safe Sequence for Transfer from Manual to Automated Lane Keeping	3	3						
Vehicle Merging	3							
Traffic Flow Control	2							
Driver/Operator Interface	4				3			

Table 8. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-In

Oper. Req.	Performance objectives		
Check-In	**Safety**	**Throughput**	**User Comfort**
Check-In (Vol.4, section 1.2.3)		-Where are vehicle system checks performed? (On-ramp transition lane)	-Are tests performed on the fly' or is the driver required to stop?
Pre Check-In Inspections & Test (Vol.4, Chap I, Section 3.1.7)	-Where will inspections occur? -What will be inspected-How will results be reported?		
Pre Check-In Inspections & Test **Vehicle Identification** (Vol.4, Chap. I)	- The status of pre check-in inspection will be conveyed during check-in	- The unique vehicle identifier will be conveyed during check-in	
Pre Check-In Inspections & Test **Destination Information**		-At check-in the vehicle will convey destination information (if entered)	
Pre Check-In Inspections & Test **Periodic Certifications** (Vol.4, Chap I)	-What is the specified time frame *for* periodic system inspections?		
Pre Check-In Inspections & Test **Check Vehicle Subsystems** (Vol.4, Chap. 1, Sec. 3.1 & 3.2)	-What vehicle systems will be checked? -What AHS systems will be checked? -What systems will be checked by a built in system test? - What systems will be checked manually?		
Pre Check-In Inspections & Test **Check Vehicle Subsystems** **Initial Self Test** (Vol.4, Chap. 1**)**	- How will the driver be notified as to the results of the check-in inspection? - In the event of failure the driver should be given detailed information on the cause of the failure.		
Pre Check-In Inspections & Test **Check Vehicle Subsystems** **Continuous Built-In Test** (Vol.4, Chap 1, Sec. 1.2)	- Continuous Built-In tests should be used to monitor the health of the system while on the AHS.	What actions will be taken for serious system failures? - Less critical malfunctions - Delineating factor between critical and non-critical malfunctions.	

Table S. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-In (Continued)

Oper. Req.	Performance objectives		
Check-In	**Safety**	**Throughput**	**User Comfort**
Pre Check-In Inspections & Test Check Vehicle Subsystems Roadside Non-Contact Testing (Vol.4, Chap. I Sec. 1.2)	- A test should be in place to assure that drivers are certified to operate on the AHS (if special AHS certification is required).		
Verification of Vehicle Registration & Operating Certification (Vol., 4, Chap. I)	- A test should be in place to assure that vehicles entering the AHS are registered.		
Vehicle systems Checks (Vol.4, Chap. 1, Sec. 3.0 - 3.2)	- Which vehicle systems will be monitored periodically while the vehicle is on the AHS? - Which vehicle systems will be inspected during the pre check-in inspection?		
Vehicle Systems Checks Sensors and Control Systems (Vol.4, Chap. 1, Sec. 3.2)	- Sensors and control systems should be tested with built-in tests. - What approaches are suggested for testing sensors and control systems?		
Vehicle systems Checks Actuators (vol. 4, Chap. 1, Sec. 3.2)	- Actuators should be tested with built-in tests - What techniques to test and verify the proper operation of vehicle actuators are used? - What monitoring techniques are used?		
Vehicle systems Checks Continuous Built-In Test (Vol.4, Chap. 1, Sec. 3.0-3.2, 4.1)	- What built-in tests will be used on the pre check-in inspection of vehicle systems? - Will these same tests be used in continuous monitoring while the vehicle is on the AHS?		
Vehicle systems Checks Roadside Non-Contact Testing (Vol.4, Chap. I)	- All monitoring of vehicle systems should be performed by the vehicle computer. The computer would communicate any failures or problems to the roadside AHS system.		

Table 8. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Check-In (Continued)

Oper. Req.	Performance objectives		
Check-In	**Safety**	**Throughput**	**User Comfort**
Vehicle Systems Checks Inspection (Vol.4, Chap. I)	Vehicle inspections need not he done while the vehicle is on the AHS. - Inspections should he performed periodically based on time and mileage.		
Check-In Abort (Vol. 4, Chap. l, Sec 34 1 t4 3)	- Vehicles that fail the check-in inspection should not he allowed to engage tile AHS.	- Vehicles that fail the check-in inspection should be directed to return to ~e manual lanes.	
Enforcement (Vol.4, Chap I)	- Rouge vehicles should be detected by the system wich would notify enforcement vehicles.		
Safe Sequence for Transfer from Manual to Automated Lane Keeping (Vol.4, Chap. I, Sec. 3.2)	- Open loop testing of the control loop should he made to verify the proper functioning of sensors and actuators.	- Once tile vehicle has passed the check-in inspection the AHS would assume control of the vehicle and move it into a platoon.	
Vehicle Merging (Vol.4, Chap. 1)	- How is space made for vehicles merging into AHS lanes? (Communication between vehicles, roadway infrastructure)		
Traffic Flow Control (Vol. 4, Chap. 1, Sec. 3.1)	- What configurations are to be used to control vehicles on the AHS during lane changing and merging? (Vehicle communication, system control)		
Driver/Operator Interface (Vol., 4, Chap. I)	The check-in interface should be obvious to use, compatible with the driving task and acceptable to drivers.		- Tests should be meaningful, unintrusive and provide the driver with understandable information regarding,' check-in failures.

3.3 Malfunction Management

Malfunction Management will have a large impact on safety, throughput, affordability and improved user comfort and convenience. The largest impact is on safety. Failure to safely and quickly handle a system malfunction or accident could result in many deaths and injuries due to the projected high speeds and small headways in the AHS lanes. In order to be accepted by society the MIS should be extremely reliable with any problems that do occur being handled safely and expediently. Failure of malfunction management will impact throughput either in the slowing or rerouting of vehicles, or in the case of a severe emergency, by shutting down the entire system. Slowing or shutting down MIS lanes would inconvenience the user by increasing the amount of time to get to their destination or forcing them to manually control the vehicle. On the other hand there must be a trade-off between the necessary reliability and convenience, and the affordability of the system. Table 9 shows the relative sensitivity of the evaluations categories to the major malfunction management design components.

Much of the information on the impact of Malfunction Management on the Performance objectives was taken from Calspan's Precursor System Analysis of Automated Highway Systems reports: Volume I, Chapter 1, Malfunction Management and Analysis; and Volume I, Chapter 2, MIS Safety Issues. Information was also drawn from Cal span's work on the IVHS System Architecture Program which was documented in a report titled "System Architecture for a Nationwide Intelligent Vehicle-Highway System; Initial Performance and Benefits Summary Report".

Table 9. Relative Sensitivity of Malfunction Management Performance Objectives to Malfunction Management Operational Requirements

Oper. Req.	Performance Objectives							
Malfunction Mgmt.	Safety	Through -put	All Weather	Enhanced Mobility	User Comfort	Fuel & Emissions	Afford-ability	Evolv-ability
Subsystem Failure	5	4					2	
Hazard Management								
Man-Made Hazards	5	4			2	1	3	
Natural Hazards	5	4			2	1	3	
Emergency Abort	5	4			2			

Table 10. Summary of AHS Design Issues within the Matrix; of NAHSC Performance Objectives by Operational Requirements for Malfunction Management

Oper. Req.	Performance Objectives			
Mal. Mgmt	**Safety**	**Throughput**	**Afordability**	**User Comfort**
Subsystem Failure	-System sensors with the ability to detect **mid** identify failures within a required time must be **verified.** (Architecture.section 4.6.S.1) -Validate **fact** that system **software has** capability to react faster and with greater precision than human operators when there is danger of a potential accident. (Malfunction Management. section 3.3.1) -Specific communication devices **must be resistant to interference and tampering to ensure that** communications only occur between valid AHS **sources.** (Malfunction Management. section 3.3.3)	- Transition from automated to manual control without dynamic disturbance to the AHS lanes must occur within a **the** period that will allow **the** system to check **vehicle components, evaluate** driver readiness to **resume control,** exit the vehicle from the **AHS lanes,** allow the driver to re-take control **and** still give the driver time to egress at the desired point from the freeway. (Safety, section 3.1.3) Provide messages **10** drivers or take automated action within 4 **minutes** of notification to the system of **an** accident or problem. This will help to prevent bottlenecks or other **accidents** that might **otherwise further reduce** throughput. (Architecture,section 4.6.S. 1) Assign **unique** identifiers to vehicles as they enter the system to prevent emergency or change commands from **being** sent to the wrong vehicles. (Malfunction Management,section 3.3.3)	Sensitive, reliable **sensors** wilt add cost to the system. A tradeoff will have to ~ made between available technology **and** affordability. (Malfunction A Management,section 3.4.3.1) **Technologies** used for subsystems should not exceed more than **5(1%** of **the** vehicle cost. **(Malfunction** Management,section,'4.1)	- **Redundancy** 0'. **Sensors will** help to improve **the** failure rate of **AHS** vehicles to **1100** to **1800** per **iii million** vehicle hours. (Malfunction Management, section 4.1) **Quick notification** of **problems caused by malfunctions** will **allow drivers** or the **system** to take **alternative** action and prevent **traffic stoppages** or **slowdowns 01)** the AHS **lanes.** (Malfunction Management, section 3.3.1)

Table 10. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Malfunction Management

Oper. Req.	Performance Objectives			
Mal. Mgmt	**Safety**	**Throughput**	**Aflordability**	**User Comfort**
Subsystem Failure (Continued)	-Use at least 2 dissimilar technologies for redundancy in critical vehicle subsystems and AHS components. In the case of an AHS component failure this will allow the AHS to continue to operate safely and continuously until the AHS component is replaced. Redundancy in vehicle systems will allow the vehicle to safely pull over in the breakdown lane, return to manual operation or continue to tile next available exit. *(Malfunction Management, section 3.4.3.2)*	- Provide at least one breakdown lane to remove malfunctioning vehicles from AHS lanes. *(Malfunction Management, section 3.5)* Note that without a breakdown lane approx. 500 to 750 lane-blocking incidents per million vehicle miles would occur. *(Malfunction Management, section,, 3.5)*		
Hazard Management Man-Made Hazards (All comments derived from *Malfunction Management, section 3.5.2*, unless otherwise noted.)	- Provide barriers between AHS & manual lanes to keep other vehicles from moving into the AHS lanes. Size, location and type need to be determined. - Consider interlocks that nullify the effect of inappropriate button presses or switch actions by the driver. *(Malfunction Management, section 3.2.4)*	- Provide maintenance vehicles that can perform maintenance to the AHS lanes or remove foreign objects without disturbing AHS lane flow.	- Cost of barriers or fences in terms of initial and upkeep investment, effect on highway land needs, cost of 24 hour maintenance vehicles. - Cost in time and driver annoyance when they fail the check-out process and are forced to go on to the next exit or go to an auxiliary lane to try exiting again *(Malfunction Management, section 3.2.4)*	- Hazards in AHS lanes could result in traffic slowdowns or stoppages or in extreme cases accidents which could greatly increase travel tine and driver stress.

Table 10. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Malfunction Management

Oper. Req.	Performance Objectives			
Mal Mgmt	**Safety**	**Throughput**	**Affordability**	**User Comfort**
Hazard Management Natural Hazards (All comments derived from *Malfunction Management, section 3.5.2,* unless otherwise no ted.)	- Consider barriers to keep animals mid other naturally occurring hazards out of the AHS lanes. Size, location and type need to be determined. - Consider alternate operating procedures involving slower speeds and backup communications for environmental hazards such as side wind gusts which saturate lateral control or lightning which knocks out roadside communication computers. *(Malfunction Management, section 3.2.3)*	-Provide maintenance vehicles to pick up or remove natural hazards such as tree In limbs, dead animals, or snow without disturbing AHS lane flow.	- Cost of initial investment and upkeep of barriers, fences or maintenance vehicles.	Natural hazards in AT l~ I m~', could result in traffic slowdowns', or stoppage or in ',extreme ~ cases greatly increasing drive times and driver', stress.
Emergency Abort	Manual backup may be totally impractical in managing a malfunction in high speed, small gap distance situations where reaction time is short and speeds are high. The system should gracefully degrade to safer situations for manual control or in cases where the malfunction is extreme, bring the AHS lanes to a halt. *(Safety, section: 3.1.3)*	- Traffic delays and/or slowdown will result. *(Safety, section: 3.1.3)* - Serious emergencies may require AHS system shutdown *(Safety, section 3.1.3)*		

3.4 Training

Training will have a large impact on the safety of the system. With training, vehicle operators will have a better understanding of how the different Systems in the car function and will use them properly and with more comfort and trust. Control center and vehicle maintenance personnel will have to be highly trained in their prospective areas of the AHS in order to assure the safety of the users and high functionality of the AHS. Table ~ I shows the relative sensitivity of each evaluation category to the major training design components.

Much of the information on the impact of training on the Performance objectives was taken from Calspan's Precursor System Analysis of Automated Highway Systems reports:

Volume 4, Chapter 5 Vehicle Operational Issues; and Calspan's Precursor Systems Analyses of Automated Highway Systems Interim Report, Task K-Roadway Operational Analysis.

Table 11. Relative Sensitivity of Training Performance Objectives to Training Operational Requirements

Oper. Req.	Performance Objectives							
Training	Safety	Through -put	All Weather	Enhanced Mobility	User Comfort	Fuel & Emissions	Afford-ability	Evolvabili ty'.
Vehicle Operator	2	2			2			
Control Center Operator	3	2						
Vehicle Maintenance Personnel	3	2						

Table 12. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Training

Oper. Req.	Performance objectives
Training	**Safety**
Vehicle Operator	-Vehicle operators must have a sufficient mental model of the AHS components in their vehicle to obtain a certain degree of self-diagnostics. This knowledge will enable the driver to understand the problem and take appropriate action if needed. *(Vehicle Poerational Issues, section 2.2)*
Control Center Operator	- Areas of needed expertise for operation and management of an AHS must be defined. The introduction of a completely new technology will require significant modification to existing practices at operating agencies in the areas of management, and operations of the AHS. Staff will need to be highly specialized and skilled in the areas of information management, communications technology, control software algorithms, and electrical and systems engineering. *(Roadway Operational Analysis. section K. 2.1)*
Vehicle Maintenance Personnel	- Considering ~e increasing number of safety-critical systems appearing in vehicles and the increase in vehicular electronics it will be necessary,' to ensure functional reliability. AHS vehicles will have to be subjected to periodic routine inspections and testing to ensure proper functionality when operating on the AHS. Maintenance personnel will need to be trained in ~e different analysis and possible failure modes of the AHS components in addition to the validation and verification of the software required for component operation. *(Vehicle Operational Issues. section 2.2)* - Maintenance staff will have to be highly trained in the use of automated ~d robotics maintenance equipment. *(Roadway' Operational .Analysis section,,* A *2.1)*

3.5 Reliability

Reliability will have a large impact *on* safety, and affordability. The biggest impact is on Safety. The failure of a main system component, such as gap regulation or lane tracking, could in severe cases result in many deaths and injuries due to the projected high speeds and small headways on the MIS or to a less extreme results if the complete stoppage of the MIS lanes were to result. Tolerance for such risks or inconveniences would limited and the AHS success would be threatened.

Although safety is very important there must be a trade-off between reliability and the affordability of the system. A system with many redundant system components would be highly reliable, but also extremely expensive. Table 13 shows the relative sensitivity of each evaluation category to reliability.

Much of the information on the impact of Reliability on the Performance objectives was taken from Calspan's Precursor System Analysis of Automated Highway Systems reports:

Volume 1, Chapter 1 Malfunction Management and Analysis.

Table 13. Relative Sensitivity of Reliability Performance Objectives to Reliability O)Operational Requirements

	Safety	Through-put	All Weather	Enhanced Mobility	User Comfort	Fuel & Emissions	Afford-ability	Evol-ability
Reliabilit y	5	3			2		4	2

Table 14. Summary of AHS Design Issues within the Matrix of NAHSC Performance Objectives by Operational Requirements for Training

Oper. Req.	Performance objectives	
	Safety	**Affordability**
Reliability	-Automation failure rate of <= I per 2000 vehicle hours *(section,, 1.4)* -Speed & Gap Control 2 redundant, dissimilar technologies with a total FPM}~I of <=300 *(section,? 3~4.3. 2)* - Lane Control - 3 redundant, dissimilar technologies with a total FPMH <=390 *(section 3.4.3.2)* -Status & Operations - subsystem with a total FPMH <=50 *(section,?* 3.4.3.2) - Malfunction Management - subsystem with a total FPMH <=140 *(section,?* 3.4.3.2) - Vehicle-Vehicle Data Link subsystem with a total FPMH <--50 *(section 3.4.3.2)* - Remote-Vehicle Data Link - subsystem with a FPMH <=50 *(section 3.4.3.2)*	-Out of 1000 *FPMH*, the automated mode must account for no more than 500 *(section* 3.4.2)

FPMH{ - Failures Per Million Hours

Appendix A

AHS Throughput Measure of Effectiveness (MOE)

- Prepared by Dunn Engineering Associates
-

A.1 INTRODUCTION

The MOEs described below are for a facility consisting of an AHS and freeway sharing the same right-of-way. They are intended to be used as a group. Taken together they represent throughput, or the capability of the facility to provide a quantity of transportation service (vehicle miles) in a time period at a reasonable speed (level of service). The relationships among these MOEs are best depicted in the graphical forms which are discussed after the MOE themselves are described.

A.1.1 Facility Vehicle Miles per Hour

Symbol: **FVMPH**

Definition: Total vehicle miles on the network MIS and general lanes. Hour to be specified by user will hours.

Purpose and Intent: Provide a measure of the provided in a given period of time.

A.1.2 Facility Vehicle Hours per Hour

Symbol: **FVHPH**

Definition: Total vehicle hours on the network above.
(mainlines and ramps) for both the typically include peak and off-peak

quantity of transportation service

Purpose and Intent: Provide a measure of the total user travel time (or delay when used in a comparative sense) for the service quantity provided above.

---

*The results presented in this Appendix are from work performed by Dunn Engineering Associates.

A.1.3 Facility Speed

Symbol: **FS**

Definition: The space mean speed of the vehicles occupying the facility described in above. Space mean speed is the arithmetic mean of the speeds of vehicles occupying a given length of highway (the facility). This is the speed associated with the fundamental traffic relationship.

$$\textbf{speed} = \frac{\text{volume}}{\textbf{density}} \qquad \textbf{(I)}$$

Purpose and Intent: Use as a measure of the quality of service for the facility Which the motorist experiences.

Relationship:

$$\textbf{FS = FVMPH/FVHPH}$$

A.2 CONDITIONS FOR USE OF THROUGHPUT MOE (2)

These MOEs are intended for comparison among planning alternatives, including the no-build alternative.

Comparisons may be performed in the following ways:

- For simulation studies, the facility demand (facility entry volumes) may be kept constant.
- For real-world traffic **evaluations,** comparisons may be made (for example for a before-and-after study) by comparison of FVHPH and FS for equal values of

FVMPH.

These types of comparisons are illustrated below.

3.0 RELATIONSHIPS FOR THROUGHPUT MOE

Figure **us** a modification of figure 2-20 in Volume III of Cal span PSA Final Report. It shows data from a simulation case study of an MIS on a freeway facility, modified to include MIS lanes as well as retaining several general purpose lanes.

The 100 percent points for the existing facility (point A) and the modified facility (point B) represent the performance for the current AM peak hour entry ramp volume.

The percentage values below 100 percent represent the performance of the roadways when the ramp volumes are reduced from peak period volumes to the indicated percentage. The same percentage of traffic from each origin to each destination was retained. It is seen that as the volumes are reduced, the performance of the roadways tends to coincide

Percentage values above 100 percent represents the performance of the roadways when the ramp volumes are increased from peak period volumes. This can be used to test the facilities' capability to service potential increased future demands. It is seen that the existing facility cannot handle more demand, increased demand simply causes congestion and queuing. The MIS-based facility can handle additional demands to 120 percent of current peak volume. At this point, additional demand results in no further increase in FVMPH, but queuing causes an increase in FVHPH (represented by line DG).

Line AC is a horizontal line at the existing facility's peak hour performance point. Line

BC, a perpendicular to line AC, represents the peak hour improvement in FVMPH, while line

AC represents the improvement in FVHPH. Line DA represents the future potential increase in

FVMPH provided by the new facility.

The slope of a line connecting the origin to any point on the curve (e.g., AF in the figure), is a measure of the speed at that point.

This type of figure provides a convenient process for evaluating the performance of facilities. While it is not possible to control the ramp demands as for a simulation, as the demand varies with time of day, the entire curve may be plotted. When this is done for both the existing and MIS facility, the measurement of the difference in FVHPH for fixed values of FVMPH provides a basis for measurement of improvement.

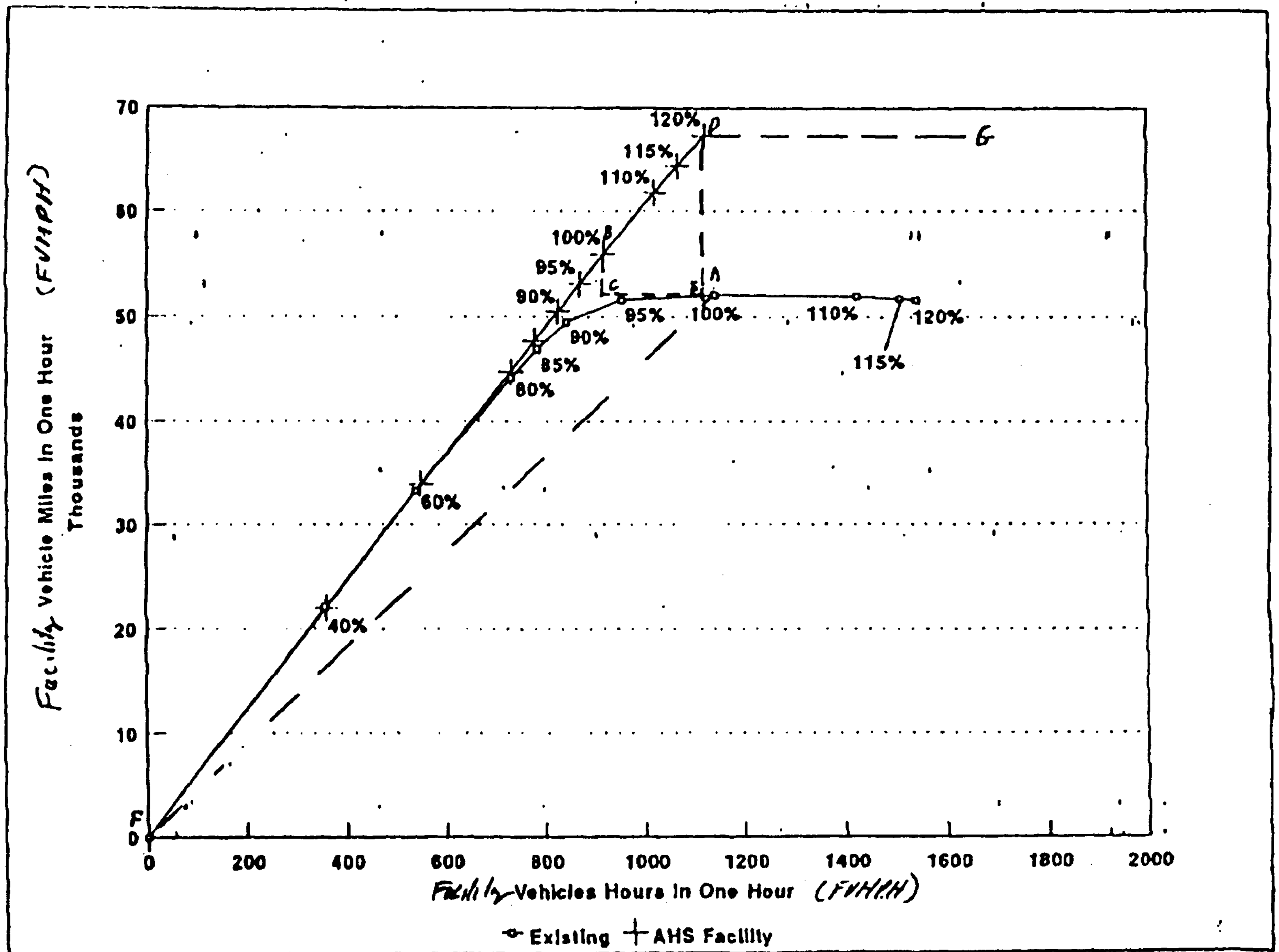

Figure A1. Throughput for Boston I-93 (Southeast Expressway NB)

A4