Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Comparable Systems Analysis

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-95-143
November 1994

PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Activity Area G

Comparable Systems Analysis

Results of Research

Conducted By

Delco Systems Operations

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.

Original signed by:

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

NOTICE

Technical Report Documentation Page

<table>
<tr><td>1. Report No.</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
PRECURSOR SYSTEMS ANALYSES
OF
AUTOMATED HIGHWAY SYSTEMS
Activity Area G
Comparable Systems Analysis</td><td colspan="2">5. Report Date</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
M. Hickman*, L. Bonderson, G. Livers**, D. Craig***, D. Lewis***, B. Culver</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Delco Electronics Corporation
Delco Systems Operations
6767 Hollister Avenue
Goleta, CA 93117-3000</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
DTFH61-93-C-00194</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
IVHS Research Division
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296</td><td colspan="2">13. Type of Report and Period Covered
Final Report
September 1993–November 1994</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Contracting Officer’s Technical Representative (COTR)–J. Richard Bishop HSR 10
* PATH, Richmond, CA; ** Delco Electronics, Kokomo, IN; ***Hughes Aircraft Company, Fullerton, CA</td></tr>
<tr><td colspan="4">16. Abstract
This activity is performed in order to derive benefits from past experience in the design, implementation, deployment, and operation of comparable systems that could be applied to Automated Highway Systems (AHS). The activity identifies 12 existing systems that share a number of characteristics with AHS. Public interaction, safety, reliability, and complexity are emphasized. Three systems, the Bay Area Rapid Transit system, automotive air bag systems, and the TRAVTEK automotive navigation system, were chosen for analysis in detail. Lessons learned in the development and deployment of these systems offer insight into appropriate techniques for technical systems specifications, verification of system performance, initial pre-deployment, quality assurance, human factors, and maintenance. Non-technical issues are also explored including the effects of political pressure and management/funding philosophy. Concerns about privacy, liability and public confidence are also examined.</td></tr>
<tr><td colspan="2">17. Key Words
comparable systems, systems specifications, human factors, political pressure, management, funding, operation, deployment, public perception</td><td colspan="2">18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161</td></tr>
<tr><td>19. Security Classif. (of this report)
Unclassified</td><td>20. Security Classif. (of this page)
Unclassified</td><td>21. No. of Pages</td><td>22. Price</td></tr>
</table>

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

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

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
INTRODUCTION 5
REPRESENTATIVE SYSTEM CONFIGURATIONS 6
TECHNICAL DISCUSSION 7
Task 1. Identify Similar Systems 7
Automated Teller Machine Systems 7
Military Communications Systems 8
Air Traffic Control Systems 8
Rapid Transit Systems 8
Airport Ground Transportation Systems 9
Automated Aircraft Landing Systems 9
Automobile Air Bag Systems 9
Ship Command and Control Systems 10
Automobile Navigation Systems 10
Air Defense Systems 10
Selection Process 10
Interaction 11
Complexity 11
Safety 11
Reliability 11
Experience 11
Environment 11
Task 2. Identify Performance Factors and Issues 13
Introduction 13
Interaction 13
Complexity 13
Safety 14
Reliability 14
Environment 14
Numerous Diverse Subsystems 15
Operation Over Geographically Wide Area 15
Failure Modes 15
Outage Constraints 15
Task 3. Perform Tradeoff Analysis 16
Task 3.1. Perform Tradeoff Analysis of Rapid Transit Systems 16
Introduction 16
Interaction With The General Public 16
Degree Of Intelligence Incorporated 16
Operation With A Severe Safety Constraint 16
Operation With A Severe Reliability Constraint 17
Environmental Constraints 17
Large Number Of Diverse Sub-Systems 17
Operation Over A Geographically Wide Area 17

Similar Failure Modes....17
Outage Time Constraints....17
Preliminary Discussion Of BART Issues....18
Technical Issues....18
Level Of Technical Sophistication....18
Level Of Technical Verification And Testing....18
Consideration of Safety and Reliability....19
Other Shortcomings In Technical Performance....19
Maintenance Requirements....19
Non-Technical Issues....20
Level Of Expectations For The Project....20
Public And Private Responsibilities In Project Development....20
Political Pressure To Bring Project Into Revenue Service....20
Market Prediction....21
Loss Of Public Confidence....21
Detailed Discussion Of BART Issues....22
Technical Issues....22
Safety....23
Specification Of Safety Requirements For System Components....24
Hazard Analysis Of the System....24
Technical Experience At BARTD And The CPUC....25
Organizational Treatment Of Safety Within BARTD....25
Capabilities Of A Safety Program....26
Reliability....26
Design For “Graceful Decay”....27
Design For Human Interaction....27
System Specification And Development....28
Pre-Revenue System Testing And Quality Assurance....28
Maintenance....29
Design For Maintenance....29
Maintenance Information....29
Maintenance Planning And Management....30
Non-Technical Issues....30
Dealing With Political Pressure....31
Interaction Of Technical And Political Forces In The Development Process....32
Ability To Develop The System Incrementally....32
Dealing With Loss Of Public Confidence....32
Level of Public Interaction Before Opening....33
Public Perception Of The Ease Of Use....33
Overcoming Early Problems....34
Task 3.2. Perform Tradeoff Analysis of Automobile Air Bag Systems....35
Objective....35
Requirement Comparison....35
Interaction....35
Complexity....35

Safety 36
Reliability....36
Environment....37
Numerous Diverse Subsystems....37
Operation Over a Geographically Wide Area....38
Failure Modes....38
Outage Constraints....38
Chronology 38
Technical Description....41
Performance....41
Air Bag System....42
Sensors and Crash Discrimination Algorithm....42
Diagnostic Unit....42
Initiator and Inflator Device....43
Bag and Enclosure....43
Wiring Harness....44
Tests....44
Crash Calibration Testing....45
Simulation Calibration Testing....46
Future Systems....46
Lessons Learned....46
SIR Development Related....46
SIR Introduction Related....48
Risks 49
Task 3.3. Perform Tradeoff Analysis of Automobile Navigation Systems....50
Objective....50
ADIS In The Market Place....50
Introduction To TRAVTEK....50
Major Functions Of TRAVTEK....51
Technical Description....51
Features of the Driver Interface....54
TRAVTEK Field Tests....55
User Studies....56
Driver Performance Studies....56
System Performance Studies....56
Driver Performance Studies....57
Yoked Driver Study....57
Orlando Test Network Study....58
Camera Car Study....58
Preliminary Results of the Evaluations....59
Relationship With AHS....60
Requirement Comparison....61
Interaction....61
Complexity....62
Safety 62

Reliability 62
Environment 63
Numerous Diverse Subsystems 63
Operation Over a Geographically Wide Area 64
Failure Modes and Outage Constraints 64
Lessons Learned 65
Programmatic And Developmental Issues 65
Introduction Related 67
Risks 68
CONCLUSIONS 70
REFERENCES 76
BIBLIOGRAPHY 78
Task 3.1 Bibliography 78
Task 3.3 Bibliography 78

LIST OF FIGURES

Figure 1. TRAVTEK System Architecture........52
Figure 2. Example Of A Destination Selection Display........53
Figure 3. Example Of A Guidance Display........55

LIST OF TABLES

Table 1. System Selection........11
Table 2. Airbag Installations Worldwide In Passenger Cars And Light Trucks........41

EXECUTIVE SUMMARY

The objective of this Comparable Systems Analysis is to identify and study existing systems that have similar characteristics to an Automated Highway System (AHS) in order to derive "lessons learned" in their implementation that could be applicable to AHS development. The Delco team identified twelve complex systems that correlated at least partially with AHS requirements. These systems included automated teller machine systems, military communications systems, nuclear power systems, air traffic control systems, rapid transit systems, airport ground transportation systems, automated aircraft landing systems, space program systems, automobile air bag systems, ship command and control systems, automobile navigation systems and air defense systems.

The ten most pertinent systems were discussed with regard to their applicability to AHS. Automated teller machines are designed to provide a high level of reliability to insure that illegal access is avoided. Their design and location has been addressed to minimize the threat to user's physical safety. The EPLRS military communication system is applicable to AHS in the respect that it is a distributed communications / navigation system that can operate with a large number of units. The Canadian Advanced Air Traffic System (CAATS) is a perfect example of a distributed control system design. The BART rapid transit system required a high degree of public support and addresses the functionality of train control systems, service reliability and safety. The U.S. Navy Link-4A automated aircraft landing system provides experience in real-time position control and safety. Automobile air bag systems have extreme performance and reliability requirements, require public acceptance, and address manufacturer liability. ACDS/C2P is a distributed ship command and control system. The TRAVTEK automobile navigation system involves a relatively complex operator interface. The United Kingdom Air Defense Ground Environment (UKADGE) is a candidate for comparison with AHS because it was developed over a ten year time frame and is a large distributed command and control system which incorporated fail-safe design techniques.

From this list, three systems were selected for a more detailed analysis based on the criteria of interaction, complexity, safety, reliability, experience, and environment. AHS will involve a very high level of operator / user interaction with the general public lacking specialized training. It involves a high level of complexity with sensing, communication, computation, and actuation. The reliability and safety of AHS must be very high. The comparable system should be fully implemented and have been in operation for at least a few years. And finally, systems designed for installation on automobiles must be designed for a demanding environment. After consideration of these factors, rapid transit systems, automobile air bag systems, and automobile navigation systems were selected for the performance trade-off analysis.

A portion of that analysis was the comparison of the three selected systems to AHS in terms of performance factors which included interaction, complexity, safety, reliability, environment, diverse subsystems, operation over geographically wide area, failure modes, and outage constraints. Pertaining to interaction, the complexity of required operator actions and user perception of system operation are relevant to AHS. The level of complexity of AHS

will be greater than other Intelligent Transportation System (ITS) deployments. The success of the AHS program will depend on high quality systems engineering. Aspects of each of the comparable systems which deal with the impact of the community of users of the system safety must be addressed. Attention to a variety of reliability factors will be necessary to ensure successful implementation of AHS. The outdoor operating environment places stringent reliability requirements on the infrastructure electronics as well as vehicle subsystems. The integration of a vast array of subsystems into a functionally flawless complete system is a concern. The system should meet the diverse needs of a large percentage of the nation’s population under diverse operating conditions. The impact of system failures to safety and system availability are primary issues. Finally, the economic feasibility of AHS will dictate a high level of system availability with graceful degradation of system operation if required.

The performance factors and issues identified by the Delco team suggest that rapid transit systems and particularly the San Francisco Bay Area BART system may be reasonably comparable to an automated highway system. As with all transit systems, the general public only has a moderate level of interaction with the system. There are considerable safety issues associated with full automation of BART, and the trains must operate under considerable reliability constraints. Environmental considerations included land acquisition, noise generation, and visual aesthetics. Many subsystems are required including vehicle, infrastructure, and centrally controlled systems. BART required considerable political consensus building and public support. Safe and prompt response to service disruptions and system failures are necessary.

A number of important technical issues that have surfaced in the development and operation of BART may be relevant for future technology options in transportation and particularly AHS. BART represented a significant opportunity to capitalize on new technologies in public transit. There is a need for a rigorous program of verification and testing for the technical performance of AHS systems. Safety and reliability aspects of the automatic system will be critical to its successful deployment. Shortcomings in BART technical performance may hold some lessons about developing reasonable expectations of AHS in both normal and degraded service conditions. Higher technology leads to much higher maintenance costs and in the case of BART, maintenance costs were due to poor workmanship and quality control.

Non-technical issues of BART development and operation were also reviewed. Contrary to initial expectations, it has had only modest impact on commercial activity in Oakland and San Francisco and has done little to alleviate traffic congestion. The BART project blurred the roles of both public and private agencies in transit systems. AHS will also bring both private and public interests into project development. Significant political pressure brought the system into revenue service well before the full system was operable and had undergone sufficient testing of technical components. As with many rail transit projects over the last 20 years, actual ridership was much lower than the optimistic forecasts. Finally, delays, disruptions and accidents resulted in significant negative publicity and led to a loss of public confidence in the safety and reliability of the BART system.

The automotive supplemental inflatable restraint system (SIR) provided a comparison of the risks in the development and introduction of AHS. The SIR is totally passive to the vehicle occupant, however, both systems have a learning period to accept aspects of the system's characteristics. They must be extremely tamper-proof and at the same time cost-effective. Similar to AHS vehicle subsystems, millions of SIR systems must be manufactured, introduced to the public and maintained in everyday use for the lifetime of the vehicle. System safety was also in the forefront of the development of SIR and was paramount to its eventual success. Since highways change infrequently, careful design analysis should be made similar to that for SIR. Both systems should be designed to have fail-safe operation. The use of automatic diagnostic recording capability for performance verification is presently being introduced in SIR systems. Such a capability is recommended for AHS, particularly for liability reasons. The SIR and AHS must perform under similar environmental conditions. Whereas SIR represents a localized sensing and actuation problem, AHS will build upon these for distributed sensing and control. Failure or outage of AHS could result in a major disruption of regional service and multi-vehicle risks.

A brief chronology of some important events on the path to industry wide installation of SIR is included in the report. Also included are the performance characteristics, a thorough description of an air bag system including such factors as the sensors and crash discrimination algorithm, the diagnostic unit, initiator and inflator device, bag and enclosure, and wiring harness. All vehicle components are subjected to rigorous tests and the SIR system must be tested in a vehicle crash environment.

The SIR trade-off analysis concluded with the lessons learned and risks. Related to SIR development, a project has a much better chance of success if it is driven by the market place rather than by regulation. Development of test and evaluation procedures is very important. Initial SIR systems were considerably more complex than later systems. The problem that both the engineering and legal communities were faced with was the inability to project what legal costs could be for the life of the project. Related to SIR deployment, a recording feature has been most useful to support legal claim investigation as well as maintenance. Despite customer initial concerns, SIR systems have become popular and hopefully AHS also will for the same reasons: the system provides safety that the general public is concerned about, education has enforced the value of the system and it is seen as the best alternative. The taxpayer must understand the benefits and want the system enough to be willing to support the cost.

An advanced driver information system (ADIS) such as TRAVTEK also provides a comparison with an automated highway system. TRAVTEK was a demonstration project to develop and deploy a full function ADIS in a limited number of vehicles and to evaluate its use by a large number of drivers. It was designed to provide assistance to the driver in location finding and navigation, destination finding, and route guidance. The project was a cooperative venture between General Motors, the American Automobile Association, the Federal Highway Administration, Florida's State Department of Transportation, and the city of Orlando.

A Traffic Management Center (TMC) collected and provided real-time traffic incident and driving time information. These computers gathered information from a number of sources including loops in the road, police departments, radio stations, and a freeway surveillance system. The TRAVTEK vehicle itself provided its current location and measured travel time.

TRAVTEK provided an in-vehicle display showing the vehicle's location and a street map, in-vehicle navigation using a combination of GPS, vehicle compass, dead reckoning, and map matching, in-vehicle address location, "yellow pages" information on businesses, attractions, and special events, optimal route selection, and turn-by-turn driving instructions. An Information and Services Center (TISC) provided information to the drivers via cellular telephone.

The TRAVTEK ADIS was evaluated in a year-long field test conducted in Orlando, Florida commencing in March 1992. General Motors provided 100 TRAVTEK equipped vehicles: seventy-five to visitors and the others to local drivers. The data collection was completed in March 1993 and the data analysis is in process with the final results available in the fall of 1994. However, some preliminary findings have been released based on user surveys and driver performance studies.

Features of TRAVTEK may logically be incorporated into AHS. The ability of the driver to receive vehicle status, platoon information, route planning, and exit information would be desirable. Driver interaction both before and after the automated phase of an AHS trip would be similar to TRAVTEK. The design guidelines that were followed are applicable. Although it did not have the complexity of an AHS, TRAVTEK was complex enough to serve as a case study for the depth of systems engineering techniques that must be applied to a complex system design such as AHS. Issues raised included the interaction of safety and liability, the integration of numerous diverse subsystems, the accumulation of a complete geographical database, and the inherent problems with vehicle-to-infrastructure communications.

Price, benefit and safety will be major concerns for an automated highway system. The highest risk for TRAVTEK acceptance was price. The evaluation illustrated that drivers liked and used the features of the system. They felt it was safe. A major challenge for AHS, as displayed by TRAVTEK, will be to keep the price commensurate with its benefits.

The goal of the analysis of these three systems: BART, SIR and TRAVTEK, was to present issues which have been addressed in the design and deployment of comparable systems in order to derive lessons learned and provide insight into design considerations relevant to AHS. Specific recommendations have been included in the Conclusions section.

INTRODUCTION

The objectives of this activity are to first identify existing systems that have similar characteristics to an Automated Highway System (AHS) in terms of public interaction, safety, reliability, and complexity and secondly to analyze several of them in order to derive benefits from past experience in their design, implementation, deployment, and operation that could be applicable to the development of AHS.

REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC's) were generated very early in this Precursor Systems Analyses of AHS program. These RSC's are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC's identify specific alternatives for 20 AHS attributes within the context of three general RSC groups.

Since the RSC's have such general applicability to these precursor systems analyses, they are documented in the Contract Overview Report.

TECHNICAL DISCUSSION

Task 1. Identify Similar Systems

The Delco team identified eight complex systems that correlate at least partially with AHS requirements as part of the initial activity planning, as documented in the activity research summary. These systems are:

- Automated teller machine systems.
- Military communications systems.
- Nuclear power systems.
- Air traffic control systems.
- Rapid transit systems.
- Airport ground transportation systems.
- Automated aircraft landing systems.
- Space program systems.

During further team discussions it was decided that several additional systems should be added to this list. They are:

- Automobile air bag systems.
- Ship command and control systems.
- Automobile navigation systems.
- Air defense systems.

Also as part of these discussions it was decided to remove two systems from the list. Nuclear power systems was removed because of the lack of experience within the Delco team. Space program systems was removed because it is not specific and many of its important aspects are covered by the other retained systems. The ten remaining systems are described in the following sections:

Automated Teller Machine Systems

Automated Teller Machine (ATM) systems have been in use since the late 1970's and are currently widely utilized by banking institutions worldwide. ATM systems may be thought of as transportation networks in which information moves from origin to destination on telephone lines or fiber optic cables. ATM networks allow system users expanded access to their funds, both spatial and temporal, as well as providing improved levels of service. Advances in computer and communications technologies have allowed for at least the partial automation of the banking industry in general and of the interaction with the public in particular. As this form of banking has become gradually more accepted by the banking customer, it has been recognized that ATM systems are required to maintain the expected high level of service as well as to reduce the overall cost of banking. The systems are designed to provide a high level of reliability to insure that illegal access is avoided and prevent any possible inconvenience to straighten out financial records. The detailed design and location of

ATM's has recently been readdressed as the use of ATM's has posed a threat to the user's physical safety as a result of assaults on people at ATM locations.

Military Communications Systems

The Enhanced Position Location Reporting System (EPLRS) is an example of a military communications system which automatically provides location of each of the reporting units using ranging measurements. EPLRS units can be carried by personnel, on vehicles, or on aircraft. EPLRS units are used for both communications and navigation. The system supports a large number of users and has position accuracy suitable for battlefield operations. EPLRS has been operational in various configurations for about seven years. The applicability of EPLRS to AHS is that it is a distributed communications / navigation system which can operate with a large number of units in a hostile environment.

Air Traffic Control Systems

An excellent example of a very modern air traffic control systems is the Canadian Advanced Air Traffic System (CAATS). This system, which is still under development, relies heavily on international standards to provide compatibility with future upgrades. CAATS consists of four major regional operations centers plus dozens of local centers. There are a number of remotely located radars and radio communications systems which must be routed to one or more centers. The applicability of CAATS to AHS is the use of current distributed control system design. At this point in time, lessons learned have not been compiled which can be applied to AHS since the system is still under development.

Rapid Transit Systems

The specified rapid transit system under consideration is the San Francisco Bay Area Rapid Transit (BART) which has been providing service in the San Francisco metropolitan region since 1974. The system was designed in the late 1950's to improve public mobility and relieve traffic congestion in the Bay area. Initially, the system was designed so that vehicle movements would be fully automated and operated from a central control center in Oakland. Vehicle control systems were required to handle train movements, especially entering and exiting stations. The central control system was also required to manage the train network, allowing control of the separation of vehicles on the right-of-way and also of the vehicle movements through track junctions. In this case, a high degree of public support, both financial and political, was necessary to develop and deploy this transit system. Through its relatively short life, BART has been the focus of controversy, stemming in many cases from concerns about the functionality of the train control system and service reliability and safety. Because BART is publicly owned and operated, there is considerable scrutiny of BART's performance in improving transportation in the San Francisco area.

Airport Ground Transportation Systems

Several airports in the United States have built or are planning to develop automated guideway systems (people movers) to move passenger traffic within the airport and between airport terminals, including: Atlanta, Orlando, Tampa, Pittsburgh, Seattle, Houston, and Dallas-Fort Worth. In shuttling passengers around the airports, these systems employ various automated control systems to move vehicles over a fixed, grade-separated guideway, often with fixed headways and dwell times at each stop. The vehicle movements usually are controlled by a central computer system, requiring only limited human interaction. Because of the significant passenger volumes in these airports, there is considerable concern for passenger safety both within and outside the guideway system. Emergency systems must respond quickly and effectively to problems on the line. Similarly, these transportation systems are often critical to passenger movements at the airport, thus requiring a high level of reliability in system performance. On the other hand, because these systems are virtually fully automated, a complex computer control system is necessary to handle both specific vehicle movements (e.g., accelerations and decelerations) and the communications and coordination among the many vehicles in the network.

Automated Aircraft Landing Systems

The Link-4A system is an automated landing system for aircraft which has been used by the U.S. Navy for over 30 years to help land aircraft on the deck of aircraft carriers. Using a carrier based radar and a two way communications link between the carrier and the aircraft, the system monitors the aircraft position relative to the glide slope, as well as the aircraft range. The system measures the aircraft position and transmits corrections to the aircraft at a rate of about 30 times per second. These corrections received by the aircraft will either automatically adjust the aircraft position or adjust indicators only, with the pilot performing the actual adjustment. The applicability of the Link-4A system to AHS is that it is a real time position control system. The safety aspects of the system are also applicable to AHS. Finally, the 30 year operational history of the system can provide some insight to the long term operational requirements of AHS.

Automobile Air Bag Systems

The automobile air bag system, also known as passive supplemental inflatable restraint (SIR) systems, is presently installed in about 90 percent of 1994 model-year cars on the driver’s side and will be installed on both the driver and passenger side of all cars by 1998. The system has required a substantial amount of testing, process- and quality-control effort, and investment in product development and cost controls. The system has high performance and reliability requirements. The crash sensor algorithm must decide the injury severity level of a crash within the first 9 to 20 msec of the crash. The system remains ready to perform its approximately 250 msec deployment process throughout a vehicle lifetime of at least 15 years. Public acceptance of this device was initially poor but with proper promotion and education has completely turned around and high demand now challenges the manufacturer’s ability to bring properly calibrated systems to market. However, even now, the public's expectation of the performance of this safety device varies so greatly that important issues of manufacturer liability are still being decided.

Ship Command and Control Systems

An example of a ship command and control system is the Advanced Combat Direction System / Command and Control Processor (ACDS / C2P). This is a distributed system which is installed on ships and also aircraft. The system relies on the exchange of peer to peer messages to allow the tracking of air, surface, and subsurface units detected by sensors on one or more ships and/or aircraft in the network. Up to 64 units can participate in the network, with up to 2000 tracks concurrently maintained by all of the units. The applicability of the ACDS / C2P system to AHS is that it is a large, distributed command and control system with a unique peer to peer protocol which allows all participants to contribute equally. This system is completing a nine year development, and is not yet fielded.

Automobile Navigation Systems

The TRAVTEK system is one of the most recently developed and tested automobile navigation systems. It has recently completed an extended demonstration on a fleet of vehicles in Orlando, FL. The system routes vehicles to a destination input by the vehicle operator. TRAVTEK displays maps as well as route instructions. The applicability of this system to AHS is that it is a vehicle based system with a relatively complex operator interface. The lessons learned regarding the operator interface problems are directly applicable to AHS.

Air Defense Systems

The United Kingdom Air Defense Ground Environment (UKADGE) is an air defense system capable of tracking objects over the entire airspace of the United Kingdom. The system control is distributed across four Operations Centers which accept inputs from radars located over the entire country. The system employs an extensive digital wide area network to interconnect the sites. This system is a candidate for comparison to AHS for a number of reasons. First, it was developed over a ten year time frame. In that time, the “state of the art” equipment selected at the beginning of the job became dated and caused a number of problems with respect to networking protocols, computer equipment and programs, and display equipment. Second, the system is a large, distributed command and control system which incorporated fail-safe design techniques to provide continuous operation in an environment where communications links, as well as radars and operations centers, could be lost at any time. UKADGE has been operational for about three years.

Selection Process

From this list of ten comparable systems three systems will now be selected for more detailed analysis. The process of selection consisted of team discussion and determination of the level to which each of the ten systems exhibit the following six criteria:

Interaction

AHS will involve a very high level of operator/user interaction. The user will be members of the general public with no specialized training. Thus interaction with the general public is stressed.

Complexity

AHS will involve a very high level of sensing, communication, computation, and actuation complexity. Thus this is a desirable attribute for a comparable system.

Safety

AHS must be designed to operate to a very high level of safety. Thus this is a desirable attribute for a comparable system.

Reliability

AHS must be designed to operate to a very high level of reliability. Thus this is a desirable attribute for a comparable system.

Experience

In order to be able to reviewed for "lessons learned" the comparable system should be fully implemented and have been in operation for at least a few years.

Environment

Systems designed for installation on automobiles must be designed for one of the most demanding environments in terms of: temperature, humidity, vibration, and operational life. Thus it is desirable that a comparable system share at least most of these severe conditions.

The results of this selection process are presented in table 1. A 0 is entered for no or very low levels of comparison, a 2 for a medium level, and a 5 for a very high level of comparison. The three systems with the highest total, rapid transit systems, automotive air bag systems, and automotive navigation systems will be studied for the remainder of this activity.

Table 1. System Selection

System	Interaction	Complexity	Safety	Reliability	Experience	Environment	Total
Automated Teller Machine	5	2	0	2	5	0	14
Military Communications	0	2	2	5	5	5	19
Air Traffic Control	0	5	5	5	0	0	15
Rapid Transit	2	5	5	2	5	2	21
Airport Ground Transportation	2	2	2	2	5	2	15
Automated Aircraft Landing	0	2	5	5	5	2	19
Automotive Air Bag	2	2	5	5	5	5	24
Ship Command and Control	0	2	2	5	5	2	16
Automotive Navigation	5	2	2	2	5	5	21
Air Defense	0	5	5	5	2	0	17

Task 2. Identify Performance Factors and Issues

Introduction

The three comparable systems selected by the Delco team will be the subject of tradeoff analysis in task 3. A portion of that analysis will be comparison of the three comparable systems to AHS in terms of performance factors which provide a basis for deriving design issues and concerns relevant to AHS. The goal of that analysis will be to establish issues which have been addressed in the design and deployment of the comparable systems in order to derive lessons learned and design considerations. In the present task, a list which identifies pertinent aspects of the comparable systems has been compiled and will be described in the paragraphs which follow. The performance factors which are covered include:

- Interaction.
- Complexity.
- Safety.
- Reliability.
- Environment.
- Diverse subsystems.
- Operation over geographically wide area.
- Failure modes.
- Outage constraints.

Interaction

The AHS may have a high degree of operator interaction, especially during the check-in and check-out processes. The level of human interface in each of the comparable systems will be defined and analyzed to derive the benefit of experience. The issues which are relevant to the AHS include the complexity of required operator actions, and user perception of system operation. User perception depends on such factors as the degree of comfort while traveling on the AHS, satisfaction with the level of service delivered by the system, and opinions concerning methods used for granting or denying access to the highway.

Complexity

The level of complexity of the AHS will be greater than other Intelligent Transportation System (ITS) deployments. The system development will incorporate diverse vehicle subsystems, infrastructure electronics and roadway structural elements, as well as local, regional, and national coordination of system functionality. The success of the AHS program will depend on high quality systems engineering in order to ensure that all aspects of the development are planned to avoid duplication of effort or the neglect of “minor” details. Implementation of formal systems engineering tools will be a significant factor in determining the efficacy of the top level systems design of AHS. Failure to establish good system engineering practices at the ground level may negatively impact schedule and/or cost.

Safety

One of the primary goals of AHS is increasing the safety of the nation's highways. Aspects of each of the comparable systems which deal with the impact to the community of users of the system safety will be addressed. Safety is more easily quantified in highway systems, since measures of effectiveness can be readily established. Such measures include fatalities per travel kilometer, accident rates, and medical insurance claims. It may be difficult to establish a basis for comparison with systems which do not involve risk of injury or death to the user. The BART system selected by the Delco team does involve the issue of providing safe service to the user, as do the TRAVTEK and SIR systems. Design considerations in each of the comparable systems will be analyzed to determine their impact towards ensuring safe operation of the respective systems.

Reliability

The issue of reliability will be an important factor in the feasibility of the AHS. Current roadway design practices consider structural reliability, but have not been concerned with the reliability concerns inherent in complex infrastructure electronics. Similarly, vehicle subsystem reliability figures are well established but the fail safe requirements of automatic vehicle control elements may exceed standard practices for redundancy. Attention to a variety of reliability factors will be necessary to ensure successful implementation of AHS. The incorporation of diagnostic capabilities for detection and prevention of failures will be a key design consideration. Fault tolerance and redundancy in subsystem elements are additional aspects which have the potential for severely impacting cost. The frequency of infrastructure and vehicle maintenance and availability of service providers will be factors in the specification of reliability requirements as well. The level of fail-safety of the system must be sufficient to achieve the degree of safety desired without compromising economical operation of the AHS.

Environment

The outdoor operating environment of the AHS will place stringent reliability requirements on the infrastructure electronics. The vehicle subsystems will be subject to the extreme range of operating temperatures, vibration, shock force, salt spray, dust, sand, chemical splash, and immersion as well as other conditions as specified for various automobile equipment locations. The high reliability requirements of the AHS in conjunction with the unfavorable operating conditions will require test specifications similar to that of both the automobile and airline industry. Test requirements and their impact to the cost of development, materiel procurement, and qualification of the system elements will be a significant design consideration. The test plans for the subsystems should be coordinated at the system level to ensure that the appropriate level of testing is performed on each element while controlling duplication of tests to avoid the high costs of military standard testing.

Numerous Diverse Subsystems

The level of complexity of the AHS will dictate an architecture which consists of a quantity of functionally diverse subsystems. The AHS will consist of system elements ranging from entry / exit structural components, to vehicle control mechanisms, to system-wide communications. The concerns which arise are related to the subject of complexity, and revolve around the task of integrating the vast array of subsystems into a functionally flawless complete system. One of the key issues will involve development of a sound system architecture which provides the optimum decomposition into functional subsystems. The interfaces between each of the subsystems should be rigorously defined, and communication among the developers of each system element should be coordinated as well. The approach used by each of the comparable system design teams will be studied and lessons learned regarding complex system integration will be noted.

Operation Over Geographically Wide Area

Full deployment of the AHS is envisioned as encompassing both urban and rural locales. The AHS has been described as the evolutionary goal of the existing Interstate Highway system, which links all 49 of the continental United States. The ability of a system to meet the diverse needs of a large percentage of the nation’s population under potentially diverse operating conditions is a pertinent issue.

Failure Modes

AHS failures may be caused by system malfunctions as well as hazards external to the system. The techniques used to mitigate system failures are key design considerations, and will be the focus of the comparable systems analysis. The impact of system failures to safety and system availability are primary issues. Techniques for preventing or reducing the severity of system failures will be of interest in the area of lessons learned and design recommendations.

Outage Constraints

The economic feasibility of the AHS will dictate a high level of system availability. The justification for implementation of this highly complex system will be the relative improvements the AHS will offer in terms of capacity, safety, and reliability over conventional highways. The tolerance for complete loss of system functionality for any increment of time will be extremely small. The graceful degradation of system operation under maintenance or other conditions will also be a prime issue.

Task 3. Perform Tradeoff Analysis

The three chosen comparable systems, rapid transit systems, automobile air bag systems, and automobile navigation systems are the subject of separate tradeoff analyses. The results are detailed in the following subsections of task 3.

Task 3.1. Perform Tradeoff Analysis of Rapid Transit Systems

This task subsection summarizes the analysis of the Bay Area Rapid Transit (BART) system as part of a comparable systems analysis of automated highway systems (AHS). The first section provides an introduction to the performance factors and issues where BART compares most easily with AHS. The second section describes a preliminary investigation of the key technical and non-technical issues surrounding BART's development and operation. The final section describes a detailed analysis of several key issues from the second section, specifically making recommendations for AHS based on the BART experience.

Throughout this report, BART is used to refer to the rail transit network and its operation. The organization which runs the transit system is the Bay Area Rapid Transit District, or BARTD.

Introduction

The performance factors and issues discussed in task 2 suggest that rapid transit systems, and particularly the Bay Area Rapid Transit (BART) system in the San Francisco Bay Area, may be reasonably comparable to an AHS. The suggested comparison addresses the following performance factors:

Interaction With The General Public

BART represents a comparable transportation system, in which some segment of the urban public is given a new transportation alternative, intended to reduce freeway congestion and improve travel times. At present, BART accommodates nearly 260,000 trips per day in the Bay Area. As with all transit systems, the general public only has a moderate level of interaction with the system

Degree Of Intelligence Incorporated

BART train operation, control, and supervision are all fully automated. Train movements in the network are under full control of a central management center using a reasonably sophisticated signal and communications system.

Operation With A Severe Safety Constraint

There were considerable safety issues associated with full automation of BART: automated and manual train control in accident or other emergency situations, hazards associated with the many car-borne components and sub-systems, safety of passengers in stations, potential failures of both train and central control systems, and other infrastructure failures.

Operation With A Severe Reliability Constraint

Under full automation, BART trains are under considerable reliability constraints: maintaining train schedules, interpreting speed commands, maintaining safe distances between trains, sensing exact location of trains in stations, and coordinating train movements at route junctions.

Environmental Constraints

BART represented a significant disruption to local communities in the Bay Area. Initially, the project involved land acquisition for the track right-of-way. In addition, BART trains generate considerable noise for local communities in the aerial and at-grade sections of track, as well as reducing the visual aesthetics of these neighborhoods.

Large Number Of Diverse Sub-Systems

Many subsystems are required for BART, including car-borne, wayside, infrastructure, and centrally controlled systems. These include sub-systems for train propulsion, automatic train operation, train detection, signaling, a fixed infrastructure and right-of-way, and a central computerized control system.

Operation Over A Geographically Wide Area

BART crosses a number of diverse geographic areas, including crossing the San Francisco Bay. Perhaps more importantly, BART operations cross a number of political jurisdictions, requiring considerable political consensus-building and public support. As a result, BART is growing incrementally, with specific corridors being added as funds and support become available.

Similar Failure Modes

Failures in the automatic train control and train detection systems have resulted in several well-publicized accidents on BART. In addition, equipment and sub-system failures require the removal of trains from service and associated disruptions in network performance.

Outage Time Constraints

Safe and prompt response to service disruptions and system failures are necessary on BART. Although fail-safe principles apply to most system outages, continued operations under degraded service conditions is critical to the system function. This need was demonstrated most obviously in the first few years of revenue service, as system problems were discovered and addressed.

Based on these performance factors, there appears to be substantial value to examining the development and operating experience on BART to derive insights for AHS development and deployment.

Preliminary Discussion Of BART Issues

An initial review of the literature with the planning, development, and operation of the BART system was conducted. From this review, a set of salient issues regarding the BART system are particularly relevant for the continuing development and deployment of automated highway systems. This section below summarizes these issues and identifies critical areas for further analysis, discussed in the next section.

There is a wealth of literature regarding the planning, development, and operation of the BART system. One could argue that BART is perhaps the most studied mass transit project in the United States, considering the very high level of scrutiny of the system during the 1970's and into the early 1980's. This literature suggests a number of important issues that have surfaced in the development and operation of BART that may be relevant for future technology options in transportation, including AHS. The relevant issues associated with BART will be highlighted and their relevance to AHS will be organized into both technical and non-technical areas.

<u>Technical Issues</u>

Level Of Technical Sophistication

The technology chosen for BART was seen as the state of the art in the 1950's. BART represented a significant opportunity to capitalize on new technologies in public transit. In order to lure travelers to the system, planners envisioned a high level of service, with headways of 90 seconds between trains and top speeds of 128 km/h. One technology proposed to reach these goals on BART was an automatic train control (ATC) system. At the time, there was little opposition to this new system, although it was untested and unproven at the time when the choice of technology was made. BART was seen as an opportunity to bring transit train control systems into the 20th century, using new and more sophisticated vehicle detection, communication, and train control technologies. Similar choices about the level of sophistication of vehicle and roadway technologies are pending for AHS.

Level Of Technical Verification And Testing

Having decided on advanced train monitoring and control technologies, both BARTD and the prime contractor (a team of Parsons-Brinckerhoff, Tudor, and Bechtel, or PBTB) developed specifications for these automatic systems. However, contracts to develop the technical systems were not always awarded to contractors with appropriately tested and proven technologies. As an example, the ATC contract was awarded to the lowest bidder (Westinghouse Electric) based on a system that had not been previously tested or demonstrated. In addition, prior to revenue service, each car-borne and wayside system was to undergo significant product testing and quality assurance. These quality standards, however, were not rigorously maintained, largely due to significant political pressure to bring BART into revenue service as quickly as possible. Similar standards and specifications of AHS systems will be developed in the near future, and there is need for a rigorous program of verification and testing for the technical performance of AHS systems.

Consideration of Safety and Reliability

In the initial act creating BARTD, the California Public Utilities Commission (CPUC) was given authority to monitor the safety of BART operations. The CPUC had limited experience with transit systems, however, and provided little oversight during the initial years of system development. In general, there were few safety standards included in the original system specifications. Moreover, PBTB, and BARTD did not have any safety, reliability, or systems engineers on the project until the early 1970's as the project moved into pre-revenue operation. The need for this capability, however, was evidenced by a large number of problems which surfaced during initial system testing. These problems included a significant number of safety issues, including unintended station run-throughs at 80 km/h, large gaps between BART cars and platforms, inadequate hand-holds for standees in the cars, and a lack of information displays for the train operator to provide service in degraded service conditions. Also, as noted above, inadequate attention was paid to product quality, resulting in considerable reliability problems with the ATC system and the cars during both pre-revenue testing and in revenue service. As with AHS, safety and reliability aspects of the automatic system will be critical to its successful deployment.

Other Shortcomings In Technical Performance

BART was originally expected to operate on 90-second headways through San Francisco and Oakland, with peak operating speeds of 128 km/h on some line segments. These objectives have not been met, largely due to safety problems with the ATC system, train and car reliability problems, lower than expected acceleration and deceleration rates, and considerable control delays at track junctions (i.e., the Oakland Wye) and at track endpoints (most notably Daly City). Moreover, BART operations have shown inadequate tolerance for faults in the system. First, as mentioned above, there was little consideration in the train cab design for information to be supplied to the train operator during normal or degraded service (e.g., location of train system malfunctions, speed limits, block occupancies, etc.). Second, there were extreme limitations on manual operation in degraded mode, restricting trains to speeds below 40 km/h and requiring significantly longer block clearances (i.e., headways) for trains. These problems caused significant disruptions to service, especially during the first several years of revenue service. This may hold some lessons about developing reasonable expectations of AHS service both in normal operation and in degraded service conditions.

Maintenance Requirements

BART's experience has reinforced the supposition that higher technology leads to much higher maintenance costs. Initially, many of the problems normally attributed to maintenance were in fact due to poor workmanship and quality control of the car systems from the supplier. At the same time, BARTD lacked the know-how on their maintenance staff to deal with train and car problems, resulting in high dependence on the car supplier. In addition, a number of studies have compared the maintenance experience at BART with other rail transit systems with a lower degree of automation. From this perspective, the experience at BARTD strongly suggests that the operating personnel and expenditures saved by employing an automated system are less than those now required to maintain the system. As AHS systems are likely to require significant maintenance of both infrastructure and vehicles, these requirements should be identified and addressed.

Non-Technical Issues

Level Of Expectations For The Project

At its inception, the BART system was intended to be a panacea to the problems of urban sprawl, decentralized commercial activity, and traffic congestion. Planners believed that this new transit system would focus development in the urban core areas of Oakland and San Francisco. This effect would be enhanced by alleviating traffic congestion in the Bay Area, thereby reducing the cost of commuting to these urban areas. As significant research by BARTD staff has reported, BART has had only modest impact on commercial activity in Oakland and San Francisco and has done little to alleviate traffic congestion. There are similar high expectations for an AHS system, which should be examined carefully to determine whether these expectations are credible.

Public And Private Responsibilities In Project Development

BARTD selected a single contractor, PBTB, for both the system design and the construction management. In this regard, the contractor team was awarded a cost plus fees contract. PBTB was answerable directly to the BARTD board of directors, leaving little oversight from BARTD staff to manage PBTB's costs or engineering practices. Moreover, there was little technical experience in rail transit systems among personnel at BARTD, leaving the lion's share of the technical oversight for the project with PBTB. PBTB also controlled contract management for all sub-contractors, many of whom were traditional defense contractors with little or no experience in transit systems. Clearly, the BART project blurred the roles of both public agencies and private firms. AHS will likely bring both public and private interests into project development, and responsibilities should be deliberately and clearly defined.

Political Pressure To Bring Project Into Revenue Service

BART ran over budget and opened for revenue service much later than expected. Delays resulted from a wide variety of causes, including construction problems, contracting negotiations and disputes, quality problems in pre-revenue testing, and arrangements for additional construction funding. Significant political pressure, however, brought the system into revenue service well before the full system was operable and before the system had undergone sufficient testing of technical components. As a result, significant degradation in service and several well-publicized accidents marred the first several years of revenue operation. AHS will also come under significant political pressure to begin operation which should be dealt with appropriately.

Market Prediction

Initial ridership on BART was much lower than the optimistic forecasts. Figures for 1975 generally show BART daily ridership on the order of 51 percent of the forecast value (133,000 actual versus 260,000 forecast). In BART's defense, however, many researchers focus on ridership trends and forecasts before the system had fully matured. Today, ridership levels are still lower than originally planned. Some reasons for this shortfall include: lack of rigor in the forecasting methods used in system planning, unanticipated growth in automobile ownership and continued low marginal costs of automobile use, poor station access, and public concerns for system reliability and safety. In this light, caution and discretion is necessary in predicting public acceptance and the demand for AHS.

Loss Of Public Confidence

During the first several years of BART operation, there were significant delays and disruptions in service mostly due to problems with the ATC system and other car-borne and wayside systems. In addition, several accidents in both revenue and non-revenue service were attributed to system failures or poor operating procedures, resulting in significant negative publicity for BART. This led to a quick loss of public confidence in the safety and reliability of the BART system. This confidence was further shaken by significant financial problems in the first several years of revenue service. The public perception of BART has slowly recovered from these initial setbacks. As with other high-technology systems, AHS will also face considerable early scrutiny of system performance, and how initial setbacks are handled may ultimately determine the success or failure of AHS.

From this initial list of issues, a number of areas were identified for further research that should provide additional insight into AHS. On the technical side, BART may offer some additional insight into appropriate techniques for technical systems specification, verification of system performance, and initial pre-deployment testing and quality assurance (The second item from the technical issues list). Given the potentially high complexity of the many systems involved in AHS, successful deployment depends critically on the ability to specify and test a highly reliable system. A related issue is the treatment of both system safety and reliability in the technical development and in system operation (The third item from the technical issues list). In addition, the level of effort required to maintain the automatic systems on BART (Fifth item.) is also investigated more thoroughly.

From the non-technical issues list, the third and fifth items are pursued in greater detail, covering the response of BARTD to continued political pressure to bring the system into revenue service, coupled with the early loss of public confidence. New technologies in transportation can come under intense political pressure as elected officials press for early photo opportunities and quick benefits to improve their political standing. The high expectations already placed on AHS ensure that the political process will have much bearing on the development and deployment of these systems. This study of BART should offer some insight into ways of dealing with the political pressure without compromising the success of the system. Furthermore, in considering the early stages of AHS deployment, safeguards are necessary to avoid quick loss of public confidence. Close scrutiny of AHS operations is unavoidable, but lessons from BART may help avoid the erosion of public trust that may seriously hamper planned AHS projects.

Detailed Discussion Of BART Issues

Following the conclusions of the initial discussion, the following section discusses in greater detail the technical and non-technical issues of greatest interest. The first section discusses the technical issues of safety, reliability, and maintenance, while the second section details the non-technical issues of handling political pressure and the loss of public confidence.

Technical Issues

There are several key points to be made regarding the technical development of the BART system. However, before going into detail on the specific issues of safety, reliability, and maintenance, it is important to make some general observations about BART and the technical development process. During development of the technical systems in the 1960's, the role of BARTD was primarily managerial as opposed to technical, and intentionally so. PBTB, the prime contractor for system design, development, and construction, was responsible for system integration and technical oversight. It was not until the system went in to pre-revenue testing that many of the technical responsibilities began shifting from PBTB to BARTD. As the reader may note, many of the problems and pitfalls noted below fall in the gray area of technical responsibility between PBTB and BARTD, often during this period of time just before the system opened.

The delegation of virtually all of the technical development tasks to PBTB meant that there was limited oversight or control by BARTD staff. This is considered by most researchers to have been the most significant error in the development of BART.[1, 2, 3] The primary problems with BART did not really stem from poor technical choices; rather, their root cause lies in poor project management and oversight on the part of BARTD. Many researchers have noted that up until the late 1960's, only one member of BARTD staff was an engineer, and he had served as a consultant to PBTB in some of their BART work prior to arriving at BARTD. Thus, there was little review of PBTB's technical work, either by BARTD or an independent review board, during the development process in the mid- to late-1960's. Such a review may have significantly improved the management of the technical development process.

> **Recommendation**: In the development and procurement of AHS technologies, a competent and independent technical review team should be retained in each phase of the technical development and testing of the system. In addition, the operating organization should hire technical personnel from the very early stages of project development.

There are several other characteristics of the technical development of BART that deserve mention. First, through the technical development process, BARTD and PBTB lacked any individuals or groups specifically assigned to the task of systems engineering. Such a group is responsible for integrating any number of complex subsystems into an integrated, operating unit. While such systems engineers are common in detailed aerospace technologies, they are relatively rare in the field of transportation. Such an organization would consider the integration of vehicle subsystems as well as the functions of wayside equipment and central control facilities. Due to the considerable development of new technical subsystems as a part of BART's development, a specific systems engineering function would have aided in system integration, in anticipating system hazards, and in responding to system problems.

> **Recommendation**: In program development as well as in each field operational test and proposed implementation, a separate systems engineering function should be incorporated that integrates AHS subsystems for the vehicle, wayside, and infrastructure.

Second, PBTB chose to use functional rather than design specifications for the development of several technical subsystems. These specifications allow characterization of a system in terms of its function, rather than determining specific equipment or other detailed design standards. These functional specifications allow the greatest level of innovation by the system developer, since they can then meet the goal of the function using any appropriate technology, with a minimum of constraints on the design itself. In the BART experience, examples of liberties taken in design include development of a (novel) train control system, development of new car technology by an aerospace contractor, and a non-standard gauge and concrete ties for the track to improve ride stability. While this may allow considerable flexibility in system design, this type of specification makes it difficult to verify contractual obligations of each system contractor when the system does not perform as desired. This was most evident when BARTD entered litigation separately against Westinghouse and against Rohr over the issue of system specifications and the resulting contractual obligations.[1, 4] In addition, the high degree of innovation in system design may also lead to difficulties in integrating various sub-systems.

> **Recommendation**: As with other technically complex systems, AHS specifications and standards should carefully balance the needs for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

Safety

During the first several years of operation, the BART system experienced a number of safety problems. Many of these problems resulted not from operator error but rather were the result of faults in the technical systems. Several safety issues first emerged in pre-revenue testing, as many of the technical bugs were worked out of the system. This period of testing was short, and as the system was rushed into revenue service, safety problems received much greater publicity.[4]

The first major accident in revenue service occurred a mere three weeks after the system opened in 1972. According to the investigation by the Legislative Analyst,[2] the car-borne automatic train control (ATC) equipment failed to identify a speed command correctly, causing the train to speed past the Fremont station and crash at the end of the line. In January 1975, a non-revenue train had a fatal collision with a maintenance vehicle; the accident was blamed on the inability of the automatic train detection system to detect maintenance vehicles, even when they shared the right-of-way with service trains. A third serious accident in 1979 involved a train fire in the Transbay Tube, burning five of seven cars of the train. Further investigation revealed that the material from which the BART cars were manufactured was not sufficiently flame-retardant.

The incidents above raise specific concerns about the treatment of safety by BARTD and its prime technical contractor, PBTB, primarily because these problems were largely the result of technical error. It seems that the root causes of these safety problems at BART resulted from a number of factors in the system development process.[4] The following suggests some of these factors and some of the lessons that can be learned about the treatment of safety in the technical development of AHS.

Specification Of Safety Requirements For System Components

The system specifications put forth by PBTB for each of the technical systems were primarily functional and not design specifications. In this way, the contractors responsible for each technical subsystem could have the greatest latitude in developing the technology, rather than being locked more rigidly into standards and existing technologies. However, this also meant that specific safety standards for each technology were basically non-existent: the technology for critical sub-systems (such as the ATC system) lacked widespread industry safety standards.[4]

Recommendation: Regardless of the decision for functional or design specifications, safety and reliability requirements for system operation should be included directly.

Hazard Analysis Of the System

Since many of the sub-systems for use in BART were developed as new technology, it would have been helpful to have a systems engineering function to determine appropriate ways of integrating these sub-systems. One part of this systems engineering function would be a complete hazard analysis of the various system components and all of their possible modes of failure. This kind of hazard analysis was performed on the car-borne and wayside ATC equipment in 1971, and identified several critical deficiencies in the system design, including the possibility of higher-than-expected speed commands on board the vehicle.[5] Unfortunately, PBTB had not investigated this matter further before the related accident in revenue service in 1972.[2, 5]

> **Recommendation**: A critical function of an AHS systems engineering group should be a detailed hazard analysis of vehicle, wayside, and infrastructure systems. This hazard analysis should be performed as early in the design process as possible to allow easier revisions to the system design.

> **Recommendation**: Safety issues should be given highest priority in determining the readiness of an AHS system before start of service.

Technical Experience At BARTD And The CPUC

The California Public Utilities Commission (CPUC) was given the responsibility for assuring safe operation of BART in BARTD's enabling legislation in 1957. However, PBTB controlled technical system specification and development up until the system opened for revenue service. Personnel at both BARTD and the CPUC during the 1960's and early 1970's had limited experience with rapid transit systems or their associated technologies.[2] Both agents may have been aided by hiring technical personnel much earlier in the technical development process.

> **Recommendation**: A staff of technically competent safety engineers should be hired (or retained) to conduct independent safety analyses for an AHS system. This staff should be brought in to the AHS project development process as early as possible.

Organizational Treatment Of Safety Within BARTD

Up until April 1972, a few months before the system opened, safety engineering was included as a small organization within the Operations department. This organization relied heavily on the technical expertise of the operations and maintenance personnel. In the view of several researchers, this did not allow a fair and independent safety review, since the operating personnel were under considerable political pressure to put the system into revenue service quickly.[2] In May of 1972, the safety group was moved to within the Finance department, creating a new Insurance and Safety organization that was at least independent of the political pressure but nonetheless distant from the technical expertise of operations and maintenance. In 1973, the group was moved up to the department level (the Insurance and Safety department), largely due to political pressure resulting from the revenue service accident and other well-publicized studies of system safety.[2] The technical competence of the safety group was still inadequate, leading BARTD to retain the Lawrence Berkeley Laboratory as safety consultants for several years after beginning revenue service.[6] It was not until July 1975 that an independent Safety Department was formed and given considerable responsibility for more technical safety issues.[7]

> **Recommendation**: A safety engineering function should include staff members at the highest possible level within the project development team, who can effectively communicate safety concerns to project management. Again, safety issues should have highest priority in system development and in preparations for the start of service.

Capabilities Of A Safety Program

Now that BART has been in operation for over twenty years, the safety organization has ultimately been given considerable responsibility and broad authority to improve safety within BARTD. The responsibilities of the BART safety program now, in full operations, may be transferable to an AHS safety organization. These tasks include:[8]

- Setting reasonable safety goals and objectives for BARTD.
- Informing BARTD management of safety status, problems, and improvements.
- Participating in the planning and review process for system design, construction, reliability, maintenance, and personnel training.
- Reviewing engineering tests to ensure compliance to safety requirements.
- Monitoring and inspection of system operation.
- Conducting hazard analyses to identify and mitigate safety risks.
- Analyzing operating rules, procedures, and practices to limit exposure to hazardous situations.
- Collecting and reviewing historical information on hazards, system failures, and accidents.
- Investigating system failures, mishaps, and accidents.
- Ensuring operability of hazard detection and warning systems.
- Ensuring compliance with regulatory agencies.
- Organizing and coordinating safety programs within BARTD.
- Conducting scheduled and unscheduled disaster and emergency exercises and drills.

Reliability

Because many of the subsystems in BART relied on new technology, it is of interest to examine how reliability was treated in system development and early deployment. The facts of the BART experience are clear: in its early years of deployment, the system was racked with problems. As late as 1975, three years after opening for service, an average of 40 percent of BART cars were out of service on a given day because of failed components. Car-borne system failures occurred very often in revenue service, seriously degrading performance not only for a given train but also across the entire BART network. Failures in the wayside ATC system also caused considerable delays. In time, however, BART has been able to recover from many of these early reliability problems, but not without public dissatisfaction with the system performance.

AHS, because it represents an entirely new technology, has very severe reliability constraints associated with successful deployment. In contrast with BART, however, an implementation of AHS may come under significantly greater pressure to ensure a high level of safety and reliability in early operation. Also, AHS may not have a long "grace period" to work out the bugs in the system. To this end, the following identifies some issues in system design and development that may provide learning experiences from BART.

Design For "Graceful Decay"

BART was intended and ultimately achieved its goal of completely automated train operation, even under degraded service conditions. However, during the first several years of operation, procedures for degraded service modes yielded significant disruptions in service. Statistics from the first three years of operation show that passengers had to be off-loaded for one out of every four equipment failures, a measure at least seven times worse than a peer group of rail transit systems. Moreover, during any car-borne sub-system failure, "fail-safe" procedures were applied; in almost all cases, this implied a full stop of the given train, after which the train was limited to a maximum speed of 40 km/h. Since there are few yards or sidings on the BART system, these trains would often continue over a significant portion of the network at this reduced speed. The frequent stops and speed restrictions resulted in serious delays in service that propagated through the system.[9]

> **Recommendation**: Consideration of automated systems should focus on a graceful decay for degraded service modes. System specifications should focus on the design issues associated with service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure.

Design For Human Interaction

As originally designed, the train operator is responsible for train operation only in the case of a major service disruption or emergency. However, because the ATC system was not fully operational when BART opened for revenue service and because service disruptions occurred frequently, the operator played a more significant role during the first couple of years of operation. This role was impeded by a cab design which assumed a much more passive role of the operator: there were no information displays in the train cab for the operator to know the intended vehicle speed or information on sub-system failures within that train. As a result, operators often used line-of-sight rules for train operation or held trains in a station for a long time to locate car problems. This was a serious design error that led to substantial train delays in early revenue service. It was several years after beginning operation before the cab interfaces were upgraded.[4, 9]

> **Recommendation**: Clearly, AHS should be sensitive to the information provided to drivers during automatic operation and especially during degraded service conditions. Human factors research should emphasize the driver's response to information especially in degraded service or emergency situations.

System Specification And Development

With some Federal financial assistance, PBTB developed a test track to test alternative system configurations. The track ultimately had two purposes: 1) to allow prospective system suppliers to test their products; and, 2) to assist BARTD and PBTB in developing specifications for each of the required sub-systems.[4] Many suppliers participated in the testing program. Moreover, PBTB often incorporated the abilities of several products tested on the track in developing the functional specifications for new sub-systems. This testing program was very successful, considering the lack of existing research and development on these systems nationally at that time.[4]

In deciding on contract awards, however, the testing experience was largely ignored.[4] Since the specifications were functional, the actual design of each sub-system was left to each contractor to define. Moreover, contract award criteria were independent of whether vendors had (successfully) demonstrated their product either on the test track or in any other application. As a result, many of the contracts were awarded to suppliers with little experience and/or no proven product. For example, the contract to supply rail cars was given to a supplier (Rohr) with no experience in rail transit, and the ATC system contract was awarded (to Westinghouse) in spite of the fact their proposed system had never been tested and no prototype existed.

> **Recommendation**: As much as possible, each AHS operational test site should be flexible to allow various manufacturers to test a variety of technologies. In selecting system suppliers, technical experience, proven technology, and test results should be given considerable weight in the selection criteria.

Pre-Revenue System Testing And Quality Assurance

BARTD had no internal quality control organization for the delivered systems.[10] As a result, operating and maintenance personnel at BARTD relied heavily on PBTB for early product testing and quality control. At the same time, political forces were applying considerable pressure on PBTB to bring the system into revenue operation; construction delays had already pushed back the opening for revenue service from 1969 to 1972. For this reason, testing and quality control functions were rushed, leaving considerable doubt regarding the effectiveness of the test procedures.[4] According to one report, less than half of the rolling stock had been subject to adequate yard departure testing, and none of the cars had undergone complete ATC system tests, prior to revenue service.[2] This inadequacy of system testing also had significant repercussions for the maintenance function at BARTD, as noted below.

> **Recommendation**: Sufficient time in the AHS development process should be left for product testing and quality control. This involves allowing ample time for suppliers to debug new technical sub-systems, as well as time and resources to test and debug the fully-integrated AHS on site before beginning operation.

Maintenance

Maintenance was the responsibility of BARTD once the various contractors began delivering each of the sub-systems. The Maintenance organization, within BARTD's Operations department, was responsible for checking car-borne systems upon arrival of the car at the yards. As noted above, the maintenance department relied heavily on PBTB to supervise these testing procedures.[3] Once revenue service began, BARTD alone was responsible for approving trains for release into revenue service each day. Because many of the delivered sub-systems had not been adequately tested for quality assurance, the maintenance function faced a considerable workload once the system entered revenue service. Anywhere from 30 percent to 60 percent of the cars were in the shop on a given day, and about 25 percent of the cars were brought into the shops three or more times with the same problem.[6, 11]

Several factors influenced the planning and management of maintenance at BARTD that can offer similar insights for AHS:

Design For Maintenance

In terms of product design, PBTB took a novel approach to specifications by including reliability, maintainability, and availability (RMA) specifications directly. Despite this approach, a number of contractors did not adequately consider product failures and maintenance requirements in designing their systems. For the cars, critical train control systems were located in very troublesome positions on the car, requiring significant time to repair or replace. The car manufacturer also did not adequately consider some of the environmental hazards of rail operations; for example, several critical components were mounted on the undercarriage, where there is considerable wear and tear in normal operation.[12] On the other hand, some components were a little too accessible. For example, the emergency door release equipment was placed just below a passenger seat, and attached only with Velcro. From that viewpoint, a passenger might accidentally (or deliberately) open the doors while the train was in motion.[10] Such problems required modification of the location of car components.

> **Recommendation**: RMA specifications should be used for any AHS implementation, including explicit MTBF and MTTR requirements. These requirements should be specified for both vehicle and wayside equipment, ensuring that parts are easily accessible and that component trouble-shooting

requires minimal effort, both on board the vehicle and in the automated lane segments.

Maintenance Information

Initially, BARTD maintenance personnel were very dependent on PBTB and its subcontractors. This occurred largely because the system specifications had been developed by PBTB and ultimate product designs were approved most often without adequate oversight by BARTD personnel.[3] Another significant problem with BARTD's maintenance efforts in the early years can be attributed to a lack of information on the built systems: significant discrepancies were often noted between car-borne systems as delivered and the blueprints on hand at BARTD. Information was inadequate, placing additional dependence on the contractors to assist in the maintenance. The maintenance effort was also poorly implemented within BARTD: there was initially no consistent information reporting format to identify problems on cars as they were brought to the shops, making it difficult to know the type and severity of the problem.[3]

Recommendation: AHS system operators should develop substantial maintenance capabilities in house during system development. Because of the large number of diverse sub-systems involved in an AHS system, capabilities should include a common failure reporting system and common information systems to track components and their specifications.

Maintenance Planning And Management

In addition to the information reporting problem mentioned above, there were initially inadequate supplies of common parts. This resulted largely from the management's inexperience with traditional inventory stocking practice. Also, because of the magnitude of initial system bugs, resources were not managed effectively. Because of the strong need to keep rolling stock on the rails, resources were funneled into crisis management, detracting from detailed trouble-shooting or other preventive maintenance practices.[11] During one maintenance audit, the ratio of hours spent on unscheduled versus scheduled maintenance was 1.48 to 1.[10] As a result, problems were not adequately diagnosed, and cars would frequently return to the shops, often with the same problem as a previous visit.

Recommendation: Again, a maintenance function should be included early in the AHS development process. The provision and maintenance of in-vehicle components will obviously be the responsibility of equipment suppliers; these suppliers should carefully consider maintenance requirements in designing and developing these systems. Infrastructure providers should also beginning planning for maintenance requirements during the development process. In both cases, requirements will include maintenance equipment to identify and repair failures, common information systems, and clearly-defined procedures for addressing scheduled and unscheduled maintenance needs.

Non-Technical Issues

The success or failure of large public transportation projects such as BART is typically driven not by the level of technical sophistication but rather by the non-technical issues. The political conditions and overall public perception of the project may have significant ramifications for its success. Because of the (often) large investment of public moneys in a project, politicians and the public alike have a vested interest in the project's outcome. The challenge to the project planners and developers is to deal with these interests appropriately. From the BART experience, it seems that if the public and political concerns for the project are not handled appropriately, the project faces an uphill battle.

In public transit projects, the loss of confidence either in the political realm or among the public at large rarely results in the full project being canceled or scrapped. In the BART case, although mistakes were made in the development process and in the early years of operation, the system operation and ridership continue to improve. This ability to tolerate short-term problems for more longer-term benefits has resulted in part from the long-term success of rail systems in other cities (Boston, New York, Chicago, Philadelphia, Cleveland, etc.). Moreover, this view of rail transit projects has led to the planning and development of other rail projects since BART. For AHS, however, no such long-term experience with the technology exists, and the early years of AHS implementation may be critical to the acceptance of this technology. For this reason, alleviating the early political and public acceptance issues will be important to sustain continued development of AHS.

Dealing With Political Pressure

The political stakes in BART that surfaced very strongly in the early 1970's were the culmination of a political process that began more than 20 years earlier. The genesis and development of BART was the result of strong political forces in the Bay Area in the 1950's. At that time, the politicians and business community supported a proposed rail system to solve the region's problems of urban sprawl, decentralized development, and increasing traffic congestion. BART served as the core element of the regional planning program. From the very outset, the political forces were sold on rather unrealistic expectations of what the rail system might do for the Bay Area.[13, 14]

The resulting political energy was compounded by the number of actors involved. Interests included local, State, and Federal officials and agencies:

- Local elected officials.
- The BARTD board of directors.
- Regional planning commissions, including the Bay Area Rapid Transit Commission (1951-1957) and the Metropolitan Transportation Commission (since 1970).
- The California State legislature.

- The Federal Department of Housing and Urban Development, or HUD.
- The Urban Mass Transportation Administration, or UMTA.

The State of California authorized legislation creating BARTD in 1957 and provided some funding for the project through the 1960's, while HUD and UMTA provided funding for the BART system development in the late 1960,s and early 1970's. Thus, a large number of political interests had a financial and/or political stake in the success of BART.

The project suffered considerable delays. The initial starting date was pushed back from 1969 to 1972, and the Transbay Tube was not opened for revenue service until 1974. Delays occurred often in the late 1960's, primarily related to the final systems design, procurement, and funding.[13] Yet, technical concerns and procurement problems with the ATC system and the cars contributed to much of the delay in the early 1970's.[2] Because of these delays, political pressures mounted to bring the system into revenue service as quickly as possible.

The high level of political expectations, the large number of players, and the project delays all resulted in great political pressure on BARTD and PBTB. Several researchers have suggested some measures which may have either contributed to or alleviated some of this political pressure.

Interaction Of Technical And Political Forces In The Development Process

During the final two years before deployment, delays in opening the system largely resulted from technical problems and debugging of delivered systems. Most researchers believe that there was insufficient time to work out these technical bugs before BART entered revenue service. Unfortunately, the technical personnel on the project (primarily at PBTB) either were not in a position to influence decision-making or simply did not speak strongly enough for a longer testing period. It seems that there was inadequate representation of technical concerns in the political process, which is largely attributed to the poor management of technical issues at BARTD.[1]

Recommendation: Technical personnel should maintain high visibility in AHS decision-making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence in AHS.

Ability To Develop The System Incrementally

One advantage of the radial nature of the BART system design is that it permitted incremental deployment. In particular, it was not necessary to have all the lines open simultaneously, but rather lines could be added incrementally. BARTD was able to open the Fremont-Oakland line first in September of 1972, alleviating at least some of the pressure to bring the system on line. This also allowed other lines to incorporate the operating experience on the Fremont-Oakland line before they opened for revenue service. Political pressure was obviously greatest to open the Transbay Tube connection from Oakland to San Francisco;[2] unfortunately, that section was the last to open, in September of 1974.

> **Recommendation**: As much as system design will allow, AHS projects should take advantage of incremental deployment. This may imply that an automated highway be deployed in a small corridor initially, allowing for system expansion to other corridors in the near future. The selection of an initial corridor should be based at least in part on the ability of that corridor to demonstrate significant first user benefits.

Dealing With Loss Of Public Confidence

For a number of reasons, public confidence in BART was shaken, especially during the first few years of revenue service. From the seemingly strong voter support in 1962, the public opinion on BART deteriorated. In early revenue service, passengers found the stations difficult to get to and encountered frequent delays and disruptions in service. These service problems were compounded by the State legislature's discovery of widespread system safety and reliability problems following the first accident, a mere three weeks after beginning revenue service.[2] Today, after almost 20 years in full operation, BART ridership is just reaching the level initially predicted for 1975.

In hindsight, there seem to be a number of factors which contributed to the deterioration of public support for BART, at least in the early years of operation.

Level of Public Interaction Before Opening

Following the voters' approval of the bond bill in 1962, the level of contact between BARTD and the public diminished rapidly. This is partly due to the obvious shift in focus toward design and construction and away from political and public consensus-building. However, as part of the BART legislation, communities could hold public hearings at any time after the vote; sadly, few communities took advantage of these hearings, except where there was considerable opposition to site development plans (e.g., in Berkeley).[15] Moreover, the responsibility for managing the public relations was passed from BARTD to PBTB, despite the fact that the consortium had little expertise in this area. At the same time, little effort was made by PBTB to solicit public comment on the project during design and construction, for fear that this would contribute additional delays and costs.[13, 15]

> **Recommendation**: AHS project development should include mandatory public forums to discuss system implementation, both before initial project authorization and during the project design and construction. In addition, other public information strategies should be implemented, such as local site offices, information telephone lines, and other avenues for both public information and input.

Public Perception Of The Ease Of Use

From the initial system design, it was clear that access to BART would be difficult, due to the large inter-station spacing. The system needed substantial in-station parking and considerable feeder bus service to provide station access for both drivers and transit-dependent passengers.[14] Parking facilities were and remain inadequate to handle demand. Moreover, for the feeder bus service, BART was largely unable to coordinate services with local providers such as AC Transit in the East Bay and Muni in San Francisco. While there were clearly stated policies regarding the level of service coordination between BART and these transit providers, little actually changed once BART opened for service.[15] For example, BART is still competing with AC Transit for passengers traveling across the Bay. The problems noted here may have resulted in part because BARTD was not responsible to any regional transportation planning body during development in the 1960's.[13]

> **Recommendation**: AHS should be incorporated in a regional transportation planning process (likely to be mandated under current Federal legislation). Specifically, adverse and beneficial impacts of an AHS should be addressed in the context of the entire regional transportation system. System development should be approved by the regional planning organization and should be coordinated with other regional transportation system improvements.

Overcoming Early Problems

Finally, BARTD officials were less than candid with the public about early problems on the system. Since much of the technical system debugging actually occurred in revenue service, there were a lot of delays and disruptions. Statistics compiled in 1979 indicated that equipment failures alone resulted in about seven failures per day, where a failure resulted in train off-loads, unscheduled train removals, and/or schedule delays over 10 minutes.[9] In addition, BARTD had significant financial problems in its first several years of operation, as revenues were unable to cover operating costs as expected.[6] From the point of view of several researchers, the first General Manager of BARTD had difficulty admitting publicly the scope of technical and financial problems within the system. As a result, the public (and the media) tended to control the investigation of these problems, rather than personnel at BARTD.[1, 6] Although there were substantial changes in management policies within two to three years after the system opened, the more gradual changes in public attitudes about BART are due to considerable patience of the public during the first several years of operation.[14]

> **Recommendation**: As much as politically feasible, problems with AHS development and implementation should be addressed candidly, both internally within the organization and externally with the public.

Task 3.2. Perform Tradeoff Analysis of Automobile Air Bag Systems

Objective

The objective of this task is to analyze the experiences and knowledge learned from the development and introduction of automobile air bag systems, also known as passive supplemental inflatable restraint (SIR) systems. Similarities and differences between the air bag system and AHS will be discussed and approaches and techniques that reduce the risk in the development and introduction of AHS will be identified.

Requirement Comparison

The SIR system and AHS will be analyzed for similarities and dissimilarities of the performance factors:

Interaction

Both the SIR and the AHS are systems which have their primary interaction with the general public as the user of the systems. However the degree and need for interaction is different and thus they are considered to only have a medium level of commonality with respect to this requirement. The SIR is a totally passive system, thus the vehicle occupant need do nothing to use the system. The AHS system will have a modest level of user interaction, for example: arrival at check-in facility, entering desired destination, provisions made for paying for the use of the system, and possibly resumption of some level of control under emergency situations. The bulk of the time however consists of no active interaction. Both systems do have a period of learning to accept aspects of the system's characteristics. With air bags many owners initially were concerned with the presence of an explosive device so close to their face and also users needed to be educated in the continuing need to use their seat belts since the air bag is by nature a supplement to the normal seat belt. Likewise the AHS user will need to be educated to accept the short headways inherent in AHS operation (RSC’s 1 and 2) as well as vehicle maneuvers which could be rather severe and unexpected during anomalous situations. Both systems should be designed to be extremely tamper-proof. Also from the point of user acceptance, both systems are dependent on public acceptance of the systems’ feature function content and must be viewed as being cost effective.

Complexity

The SIR and the AHS have a medium level of correlation for the level of their sensing, communication, computation, and actuation complexity. Few systems conceived by engineers have the level of complexity inherent in the AHS. The SIR system could be classified as similar to one subsystem within a vehicle’s AHS equipment. To the extent that millions of the systems have to be manufactured, introduced to the public, placed, and maintained in everyday use for the useful lifetime of a vehicle, the two systems have commonality. Designing for minimum complexity is difficult because each component, circuit, or mechanical part should be analyzed to identify multiple applications whenever possible. This design approach is foreign to most engineers and will add significant cost to the design phase. Most on board vehicle designs go through an evolutionary process taking several iterations before an efficient fully developed product is achieved. Vehicles are replaced fairly often, therefore, evolutionary optimization occurs in a relatively short period. Highways on the other hand do not change frequently, therefore, their design should be very carefully analyzed, with several pilot test tracks built and tested, before commitment to a large scale construction project can be made. These last considerations are more severe for an infrastructure intensive implementation such as RSC 1 and for RSC 3 to a lessor extent.

Safety

The SIR and the AHS have a high level of correlation for the degree to which safety is an important performance factor. At first consideration, the two systems may not seem to have such a level of commonality. SIR is first and foremost a safety device, designed to enhance occupant safety in the event that the vehicle becomes involved in a class of very unsafe dynamics. The AHS on the other hand is intended to introduce a high level of driving automation while still maintaining or even improving on the generally safe use of vehicles on freeways. Thus AHS, while having the potential to enhance safety, could, through malfunction, be responsible for degrading safety in isolated instances. For this reason, safety should be the primary requirement of the total AHS system with emphasis on the fact that the system should be suited for use by the general public and not trained expert users.

Total system safety was also in the forefront of the development of SIR and was paramount to its eventual success. Extensive testing was done to insure that inflator toxicity, hearing damage from deployment noise, occupant injury due to bag inflation, waste disposal issues, immunity to rough and abusive system treatment, public hazard due to vehicle fire, and etc. were demonstrated to be benign before the system concept was even considered for a technology demonstration.

Both SIR and AHS should be designed so that all safety related failures are diagnosed. Each safety related system should contain sufficient diagnostics sensing to permit monitoring, on a real time basis if possible, or if not, at least as part of the check-in procedure. Extensive failure modes and effects analysis (FMEA) should be completed before engineering development units are built for evaluation. This analysis should not be overlooked until the design is frozen and then rushed through with little regard to optimizing the design for safety. The design team should be organized so that those responsible for the FMEA and system safety have change control of the design. Anomalies pointed out as a result of FMEA analysis should be resolved before any production hardware design is finalized.

Reliability

The SIR and the AHS systems have a high correlation for the reliability performance factor. Both systems must be designed to be “fail safe” in operation. The SIR reliability requirement is in the .9995 to .99995 range. This level of reliability for a system as complex as the AHS would be very difficult to achieve. Careful thought and analysis should be given to this issue before a reliability requirement is defined. Any approach should incorporate monitoring and diagnostics as discussed under Safety in order to achieve an acceptable level of reliability when in use. However, reliability can not be achieved at the expense of a frequent need for service. In particular, false diagnostics should be avoided to prevent the onset of a casual attitude on the part of both service technicians and owners. The use of automatic diagnostic recording capability for performance verification is presently being introduced in SIR systems. Such a capability is desirable for AHS, particularly to protect against bogus product liability claims. Liability issues are the legal side of the technical issue of reliability and safety. As illustrated by the recent lawsuits against General Motors on the issue of the safety of side mounted fuel tanks, an automobile manufacturer may still face legal issues of liability even when its products meet all applicable Federal Motor Vehicle Safety Standards (FMVSS) regulations in place at the time of manufacture. Manufacturers and installers of AHS equipment could formulate more positive business plans in an environment of known liability exposure.

Environment

The SIR and the AHS system have a high correlation for environmental performance factors. The correlation is not perfect since not all of the AHS system equipment is mounted in or on the vehicle, whereas all of the SIR components are on the vehicle. This factor is most important for the vehicle centered configuration, RSC 2. However, even the infrastructure centered RSC 1 has a significant complement of vehicle mounted equipment The automotive environment is codified in SAE J1211 – “Recommended Environmental Practices For Electronic Equipment Design”.[16] This specifies test methods and environment extremes for: temperature, humidity, salt spray atmosphere, immersion and splash (water, chemical, and oils), dust, sand, and gravel bombardment, altitude, mechanical vibration, mechanical shock, factors affecting the automotive electrical environment, steady state electrical characteristics, and transient, noise, and electrostatic characteristics. All factors considered, the automotive environment is one of the harshest and most demanding with regard to the location of equipment. As an example, common industry electronic parts for control modules are temperature rated for -40 to 125°C at their mounting junctions. The most benign location for the mounting of such modules is the vehicle trunk where the design temperature is -40 to 85° C. The module, however, is internally dissipating 10 to 20 watts or more depending on the internal components and, in particular, the number and type of output drivers. Insuring that the internal temperature does not exceed 125°C can be a major design challenge.

Numerous Diverse Subsystems

The SIR and AHS have a medium level of correlation for this performance factor. The SIR system consists of only about seven subsystems: one to several crash detectors, a crash discrimination algorithm, a diagnostic unit (including backup power), an initiator and inflator device, a nylon bag, a module enclosure, and a wiring harness. This is a mini-version of the parts necessary for AHS on board a vehicle with the exception of communications. Since an AHS equipped vehicle must communicate with the infrastructure and other vehicles (to varying degrees based upon the specific RSC) the comparison becomes only partial. Also the

AHS will have far more components in its total vehicle system. SIR represents only a localized sensing and actuation problem, while AHS represents a distributed sensing and control problem. Even the type of sensing is fundamentally different. The SIR requires the velocity change of the vehicle structure relative to the occupant. This is accomplished quite simply with classical accelerometers consisting of a suspended mass which deflects in proportion to its acceleration. The acceleration is then integrated to compute the velocity change relative to the occupant. The AHS in addition to acceleration must sense its velocity and position relative to other vehicles as well as the wayside. This requires some form of reference, either active or passive, and introduces a completely different set of sensing problems to be overcome.

Operation Over a Geographically Wide Area

The SIR and AHS systems have no correlation for this performance factor. Even though both do indeed operate over a geographically wide area, the SIR system has no knowledge of its location. As discussed under the previous performance factor, the only sensing is that of absolute acceleration and there is no communications except between the subsystems of a single vehicle's SIR system.

Failure Modes

The SIR and AHS systems have only a low correlation for this performance factor. Some of the failure modes of the various system components may be similar. However, the consequence of those failure modes is very different. SIR failure modes result in the absence of a vehicle safety system that by its presence enhances the safety of the vehicle. On the other hand many of the AHS failure modes would result in the direct occurrence of an unsafe situation that would immediately place the vehicle occupants at considerable risk. In the SIR system failures are sensed and diagnosed in order to provide a reliable safety enhancement. In the AHS system all failures should be sensed and reacted to in order to maintain vehicle safety.

Outage Constraints

The SIR and AHS systems have only a low correlation for this performance factor. Outage of a SIR system impacts only the safety enhancement of the one vehicle involved. Outage of AHS systems either on a vehicle or the infrastructure could result in anything from a small degradation of system service, to major disruption of regional service, and could place one or more vehicles at risk.

Chronology

The air bag is just one of literally hundreds of safety related improvements and systems which have been introduced on the automobile during its long history. From the first speedometer in 1901, to self-starters, hydraulic brakes, self-canceling turn signals, seat belts, padded dash and sun visors, up to the present wide installation of antilock brake systems and air bags, vehicles have continually evolved. Many features taken for granted today were first introduced as safety advances. The following is a brief chronology of some important events on the path to industry wide installation of air bags:[17, 18]

- In 1924 General Motors opened the automotive industry's first private proving grounds where safety related and other development work can be performed in a controlled repeatable manner.

- In 1934 General Motors conducted its first rollover and barrier impact tests.

- In 1937 the automotive and allied industries, through the Automobile Manufacturers' Association, organized the Automotive Safety Foundation to improve traffic safety, stimulate accident research, and disseminate information on safety related issues.

- In 1953 American auto manufacturers began voluntary crash worthiness testing of instrumented structures and dummies.

- In 1955 General Motors first provided an optional front seat belt.

- In 1956 Ford introduced the "Life Guard" safety package. The option included padded dash and sun visors, recessed steering wheel hub, and seat belts. Later, Ford General Manager Robert McNamara told a congressional committee that public acceptance for the option had been poor even though it was offered at cost, and Ford had heavy losses associated with making this package available.

- In 1966 the National Highway Traffic Safety Administration (NHTSA) was formed to regulate safety on the nations highways.

- In 1967 component suppliers and various research organizations began development of air bag components and systems in anticipation of some form of safety regulation.

- In 1969, FMVSS 208 – Occupant Crash Protection-Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses,[19] was initially introduced. This regulation set the requirements and guidelines for a passive occupant restraint to be installed on vehicles by 1972. The air bag concept was thought by many investigators to be the best technical passive restraint concept for meeting the regulation.

- In 1972 the effectivity date of FMVSS 208 was delayed, however component suppliers continue development work on air bags..

- From 1973 through 1975 General Motors offered an optional full frontal air bag system on several vehicles. The option was unpopular with customers and was discontinued after 10,000 systems were sold.

- In 1976 the effectivity for FMVSS 208 was changed to 1981. Air bag development began again.

- In 1981 the effectivity of FMVSS 208 was canceled but European development of air bags continued.

- In 1983 the Insurance Institute for Highway Safety (IIHS) lawsuit against the NHTSA for cancellation of FMVSS 208 was found in favor of the plaintiff. FMVSS 208 was rewritten to require phase-in of passive restraints (automatic belts or air bags) starting in 1986 and complete compliance by 1990. Development was reinstated throughout the industry.

- In 1984 Mercedes Benz introduced optional, all electronic driver's side air bags in U.S. vehicles.

- In 1986 Ford introduced driver's side air bag on two vehicle lines. Mercedes Benz introduced driver's side air bags as standard equipment for all U.S. vehicles.

- In 1987 Ford petitioned NHTSA to delay the full frontal passive restraint requirement of FMVSS 208 if an air bag is installed for the driver's side. This petition was motivated by technical difficulties involving large passenger bag installations and out of position passengers as documented in tests. NHTSA supported Ford's petition and permitted installation of active belts in driver's side air bag installations until 1994. Also in 1987 American manufacturers began the development of a fully electronic air bag system.

- In 1988 Chrysler introduced its first optional driver's side air bag. General Motors began supplying optional driver's side air bags again.

- 1990 was the first year for 100 percent passive restraint participation for vehicles sold in the U.S. Most U.S. and European manufacturers utilized driver's side air bags in at least one vehicle platform. Asian manufacturers generally elected to introduce standard passive belts.

- In 1992, FMVSS 214 – Side Impact Occupant Protection regulation was introduced. This could be a potential air bag application but can also be addressed with side reinforcements. This regulation will become effective in limited numbers for model year 1994.

- In 1993 the first all electronic air bag system was introduced by American manufacturers.

- In 1994 the full frontal passive restraint requirement was reinstated to begin a three year phase in. By September of 1996, all front seating positions of cars are to be protected with air bags and active seat belts. (Note that active seat belts mean active participation by the occupant to apply.) This applies to 95 percent of each manufacturer's fleet. One year later a similar requirement must be met by 80 percent of each manufacturer's fleet of light duty trucks.

- In 1994 South Dakota and Kentucky become the 47th and 48th States to pass legislation mandating the use of seat belts.

More than thirty years have passed from the introduction of FMVSS 208 until the full implementation of air bags. Today, both consumers and manufacturers recognize the value of air bags. The North American market has the widest use of air bags but the rest of the world's vehicle production is following as indicated in table 2.[20]

> **Recommendation:** The introduction of a pervasive consumer oriented system such as AHS needs the highest degree of coordination between government, manufacturers, consumer needs/wants, and technical state-of-the-art. The public perception of the use, benefits, and operation of a system is fundamental to market place acceptance.

Table 2. Airbag Installations Worldwide In Passenger Cars And Light Trucks

	Driver-Side Installation (Percent)		Passenger-Side Installation (Percent)	
	Year 1993	Year 2000	Year 1993	Year 2000
North America	52.7	99.9	24.8	99.8
Mexico	11.2	48.0	6.3	48.0
Western Europe	18.9	75.5	9.8	75.5
Asia-Pacific	20.0	56.0	7.6	56.0
World	30.2	76.2	14.0	76.2

Technical Description

The following is a description of technical aspects of SIR in the areas of performance requirements, system composition, required testing, and future trends.[21, 22]

Performance

In general, an air bag should not deploy in a frontal collision up to about 16 km/h and should always deploy in a collision of more than 24 km/h. Angle , pole, and road obstacle collisions have different and more complex criteria. Within about 15 msec of the start of an impact, the air bag system's deceleration sensors and crash discrimination logic should decide the severity of the impact and whether to deploy the air bag. In about 3 additional msec a pyrotechnic squib fires and the generated gas begins to fill the bag. Within about another 30 msec the vehicle occupant collides with the fully inflated air bag and for the next 50 msec rides the bag down as the vehicle completes its collision. Studies show that this fairly simple but highly reliable, fast acting, but long lived device can decrease crash deaths in front and front-angle crashes by about one fourth. This life saving action is not without some negatives. Occupants can receive abrasions, cuts, burns, and eye injuries as they collide with the air bag. Deployment also results in about $1200 of vehicle repair expenses in addition to the other crash damage. Thus it is critical that the air bag be deployed only when it is needed to prevent or lessen more severe occupant injury.

Air Bag System

The air bag system consists of: one or more deceleration sensors, a crash discrimination algorithm, a diagnostic unit with backup power, an initiator or squib, an inflator device, a nylon bag, an enclosure, and a wiring harness. Present systems incorporate significant differences in features such as the crash discrimination algorithm, patterns used in folding the bag, pressures and rates of bag inflation, methods for venting the bags , and materials used for the components

Sensors and Crash Discrimination Algorithm

The first generation systems used several electromechanical sensors mounted at various locations towards the front of the vehicle. These were usually wired in parallel but in series with an arming sensor set to a fairly low detection threshold to prevent deployment in response to jolts not related to collisions. These sensors were simple on/off switches biased to a calibrated deceleration level and incorporating damping to prevent oscillations of the moving mass. The multipoint arrangement of sensors was necessitated by the need to reliably sense frontal, angle, and pole crashes which have varying patterns of vehicle body deceleration. The crash discrimination logic was inherent in the parallel/series wiring patterns and the biases and tolerances of the sensors. In such a system, the several electromechanical sensors constituted a significant fraction of the total system cost.

The designs of second generation systems have been driven by the desire to reduce cost while achieving comparable or even better crash discrimination. In these present systems, a single-point deceleration sensor is used. This sensor produces an output signal proportional to deceleration at the sensor. For cost reasons and to protect the sensor from the hostile underhood environment, it is desirable to mount the sensor in the system diagnostic controller or even integral with the air bag. This has also allowed the present and future introduction of state-of-the-art sensors of various designs such as piezoelectric, ceramic, and even micromachined silicon. In order for a sensor located more remotely from the front of the vehicle to measure deceleration accurately, it has often been necessary to redesign portions of the car structure. The structure must transmit the crash pulse quickly and accurately to the mounting location of the sensor. Thus the air bag system is now totally integrated into the total vehicle system. The crash discrimination logic consists of processing the deceleration signal in a microprocessor based digital algorithm. These algorithms have evolved to the point where they are predictive rather than just sensing algorithms.

Diagnostic Unit

All air bag systems have some form of diagnostic unit. At the minimum it is necessary to constantly check the system for basic connectivity integrity. As second generation units incorporate microprocessors for the crash discrimination processor, it has been possible to incorporate additional diagnostics in this processor. As the cost of microprocessor memory has decreased, it is common practice to incorporate some amount of recording of sensor signals. This is routinely done for diagnostic messages to assist in maintenance and has now been extended to the recording of sensor signals during a crash. This information can be used to reconstruct the actions of the system and can be invaluable in the event of litigation surrounding a particular crash. Since a crash could disrupt power from other vehicle systems, a backup source of energy in the form of a capacitor is included in the diagnostic unit. This stored energy can be used to power the system during a deployment event if needed.

Initiator and Inflator Device

Sodium azide propellant in pellet or wafer form is the standard gas generator for inflating the air bag. The rate of gas generation is determined by varying the form of the pellets to control their surface area. When a deployment is desired, an electrical spark is created at wires in contact with a small quantity of initiator pyrotechnic material, which then ignites the sodium azide. The sodium azide combustion produces large quantities of nitrogen gas. This pressurized gas leaves the inflator device and inflates the air bag in 20 to 40 msec. The combustion of the sodium azide also produces sodium, which of course is very toxic to humans. To prevent the formation of free sodium, the sodium azide is mixed with chemicals that produce sodium salts on combustion. The generated gas also passes through a filter before exiting the inflator device. This filter removes combustion particulates and contains additional chemicals which tie up most of the remaining free sodium. Manufacturers of the inflator devices continue to look for alternatives to sodium azide because its use has several negative aspects which must be carefully controlled. One of its undesirable characteristics is the fact that when it contacts water in its solid state, it becomes a hazardous carcinogen. Thus the recycling and ultimate disposal of air bag units becomes problematic.[23]

Several alternative designs for the inflator device have been studied. An early design used stored pressurized gas to inflate the air bag. The nominal design temperature extremes for the instrument panel are -40° C to 85° C, with even higher specified for the top surface. For such a wide range of ambient temperature, the inflation performance using pressurized gas is unacceptable. A hybrid design has been made which uses both stored pressurized argon gas and a small charge of pyrotechnic. The pyrotechnic is burned to heat the stored gas to a more uniform temperature just before the gas is discharged to inflate the air bag. This has the advantage of requiring less pyrotechnics and minimizes the generation of sodium. However, earlier designs suffered a size and weight disadvantage compared to the standard design. These design issues have been addressed and hybrid inflators are now being installed in selected applications.

Bag and Enclosure

All current air bags are made of nylon but do vary as to the specific type and weight of nylon. The driver side unit is circular, consisting of two circular pieces stitched together. The volume is approximately 60 liters. Many are coated with a neoprene or similar material to seal the bag and to provide protection from the heat of the pyrotechnics. The passenger side unit is more complex to make. They are typically three to five times larger in volume and more likely are not coated. The passenger side unit has received considerable detailed dynamic modeling because of more demanding requirements. It should provide protection for two front seat passengers and is often required to expand up and off a combination of instrument panel and windshield surfaces. In addition, whereas the driver is usually centrally located in front of the steering wheel, the passengers ranging in size from children to adults, may be sitting in various positions and are usually further from the point of mounting the air bag. These requirements result in a passenger side air bag which is more uniquely designed for its specific application and which is inflated at a different rate than the driver side unit.

Air bags are packed into the inflator modules by folding the bag material in various patterns. A number of different fold patterns are used. The specific pattern used strongly influences the bag inflation speed and the uniformity of that speed. Vents are located on the rear of the bag. The size and detailed design of the vents is chosen to control the deflation characteristic of the bag. This is critical for occupant protection as the person rides the bag down during the crash event.

Finally, the air bag and inflator device is protected by a polyurethane or other plastic cover. This is designed to tear easily along scored lines during the air bag deployment. However it should visually blend with the automotive interior and be durable enough to withstand 15 years or more of normal interior vehicle use.

Wiring Harness

The wiring harness provides the system's electrical connectivity. This seemingly simple component receives much design effort within the industry because of its cost, difficulty of installation, and potential for connection defects. Significant simplification of the wiring harness is also one of the desirable features of the second generation systems which have one deceleration sensor mounted contiguous with the diagnostic unit.

> **Recommendation:** The development of AHS systems will likely follow the trends of automotive systems such as the air bag with respect to the driving developmental influences, which are:
>
> - First generation systems are driven by the need to provide features which are pleasing to the customer, incorporate desirable technical, diagnostic, and service functions, meet overall cost targets, and meet applicable legislative requirements.
> - Second generation systems continue to meet the first generation requirements while also placing increased emphasis of cost and packaging considerations (size, shape, weight, and location).

- Third generation systems meet all earlier generation requirements while also meeting the need to integrate functions both within the system and with other systems and addressing concerns for the recycleability of system components.

Tests

All vehicle components are subjected to rigorous tests under many and varied conditions. SAE J1211 – "Recommended Environmental Practices For Electronic Equipment Design"[16] provides details on the environment to which electronic components are routinely specified and tested. All mechanical components have similar severe environmental requirements. Testing is performed on individual components, on vehicle systems, and finally on total vehicles. Prototype hardware must be available with a lead time which is sufficient for full four-seasons testing and durability testing prior to release to pilot and finally production. In addition to this normal form of testing, SIR systems must be tested in vehicle crash environments.

There are an infinite number of crash scenarios that can occur to a fleet of vehicles. One of the first tasks required for SIR development was to attempt to classify crash scenarios into a few general categories that can be replicated by one or two crashes per category. Many of the crashes must be performed long before production or even pilot versions of new vehicle platforms are available. These crashes must use hand built bodies which are very expensive. Other vehicle equipment such as engine mounts, seat structures, steering columns, and aspects of the basic body structure design also require crash tests as part of their design process. These other equipment tests tend to be simple forward barrier tests at 48 km/h. Thus there is usually the opportunity to perform multiple tests on one crash for this particular category. There is a strong cost incentive to keep the number of crash tests to a reasonable number. Early SIR development efforts required on the order of a hundred crash tests before a system was considered to be ready for vehicle platform production release. That number has since been reduced to a few dozen tests for each new vehicle platform.

Crash Calibration Testing

SIR calibration crashes are divided into three basic categories: first there are crashes required to certify compliance with FMVSS 208, secondly there are crashes required to demonstrate additional "real world" crash conditions, and finally these are tests needed to demonstrate acceptable performance under abusive treatment.[24] These last two categories of tests are self imposed by the manufacturer and are designed to meet requirements which the manufacturer feels are needed to provide what is called due care for his customer. The FMVSS 208 in summary requires that several test criteria as measured using a specified instrumented crash dummy[25] be within an acceptable value for several types of crashes. Those crashes are: frontal collision into a barrier at speeds up to 48 km/h and at angles up to 30 degrees off perpendicular, lateral moving barrier crash at speeds up to 32 km/h, and lateral rollover at speeds up to 48 km/h. SIR by its nature provides protection primarily for the frontal crashes and the seat belts provide protection for all the crashes. Thus only frontal crashes will be continued to be discussed. The manufacture specified tests are: crashes at lower velocities up to which the SIR should not be deployed since it is undesirable to deploy the SIR if serious injury is not threatened, crashes representing collisions in several ways into poles and animals, and car to car crashes that include a range of angles and variations on head on and offset orientation. The abuse tests are conditions for which the SIR should not deploy and include: driving on several categories of rough road, impacts with curbs and chuck holes, hammer blows to the bumper and other body parts, and severe door and hood slams. The manufacture specified tests also vary somewhat from platform to platform since the specific engineers in charge of the platform development exercise a degree of control over the specifications for their platform.

Simulation Calibration Testing

The simulation of vehicle structures exposed to various crash scenarios is an area of extensive research. Major advances have been made but the results have had only limited direct application in the calibration of SIR sensors and algorithms. The underlying problem is that the details of real world crash dynamics exhibit considerable variation. The acceleration as sensed at the same location of two nominally identical vehicle platforms crashed in the same way can often vary by as much as 10 to 30 percent. The primary use of simulation to date has been to record the acceleration signals at candidate sensor locations for the above described categories of crash tests and then use those signals as inputs to simulated models of the sensors and algorithms. In this manner, the necessary sensor location and calibration set in combination with the crash discrimination algorithm parameters can be determined which will satisfy all applicable deployment criteria. Even then, the variation of crash test data has often resulted in the need to repeat costly tests to prove that an anomaly from one test is not repetitive.

> **Recommendation:** Systems which have an overriding impact on safety obviously require extensive testing. It should also be realized that the formulation of test procedures, standards, and specialized instrumentation requires long lead times which can be comparable to the system development time.

> **Recommendation:** Test and evaluation procedures should be a mix of actual testing and simulation to span all possible response scenarios.

Future Systems

The following are some of the areas where advances can be expected in future air bag systems:

- Increasingly sophisticated crash discrimination algorithms.
- Smart air bags which are deployed at rates selected to optimize protection for the specific crash, seat belt use, size of occupant, and closeness of the occupant to the air bag.
- Systems which can be retrofitted to vehicles without air bags but which offer less than original equipment levels of protection.
- Rear seat air bag systems.

- Air bags which offer protection in side impact collisions, particularly at the head level.
- Disarming of passenger side systems when no passenger is present or severely out of position passenger is detected.[26]

Lessons Learned

SIR Development Related

A project has a much better chance of success if it is driven by the market place rather than regulation. Air bags would not be in cars today if it were not for the demands of the marketplace. FMVSS 208 (until recently) never mentioned air bags, only passive restraints. The passive system requirement could have been met either by the use of belts, air bags, or a combination of both. The latter concept (and the best performing) emerged even though it was the most expensive, primarily because of market demands. If left up to the automobile manufacturers, optional active belts may have been the only occupant safety equipment provided to the motoring public because of competitive constraints.

Development of test and evaluation procedures is very important. New emerging AHS technologies have the same problems today that the occupant protection researchers had 25 years ago when that technology was in its infancy. There are an infinite number of “real world” risks and hazards that can occur to a vehicle. It would be virtually impossible to test for every possible condition or scenario that a vehicle will ever encounter, therefore new and creative analyses need to be developed along with complex mathematical simulations in order to simulate most of the “real world” conditions.

Simulations should also be validated to demonstrate that the answers given by a simulation at least match some of the actual test results, either on a one for one comparison or on a statistical basis whichever is appropriate for the dynamics being simulated.

Initial SIR systems were considerably more complex than later systems. Early systems included features thought to be necessary such as redundant accelerometers, uncommanded deployment diagnostics, arming sensors, and etc., that were later dropped. The tendency towards system complexity was largely driven by a lack of understanding on the part of engineers as to what was necessary to adequately protect the manufacturer from product liability suits.

> **Recommendation:** A complete AHS system requirements specification is necessary at the beginning of the development process. This specification should be the focus of strong scrutiny in order to avoid creating an unnecessarily complex system.

Numerous attempts were made to perform trade-off studies which compared value added for various features and combinations of features. The problem that both the engineering and legal communities were faced with was the inability to project what legal costs could be for the life of the product. Thus it was very difficult to place a real value on those hardware and software countermeasures which were being studied for inclusion in the system. AHS will be faced with the same dilemma except that it will deal with many more systems. One task that the AHS design team should investigate is to define a method of metrics that could be applied to each subsystem. These metrics would assist in the development of a liability budget for use in evaluating the value added to incorporate countermeasure hardware and software features.

> **Recommendation:** A liability budget should be firmly established early in the AHS development process. A manufacturer needs to clearly understand its liability exposure in able to properly budget the cost of liability into the AHS system's business case.

This complexity and related high cost caused customers to question the merits of the added redundancy. Pressure in the market place to reduce costs were so strong that system costs were eventually cut by a factor of approximately two thirds.

<u>SIR Introduction Related</u>

Initially some customers were concerned about locating an explosive device near their face and the possibility that it might have an inadvertent deployment. Further deployment concerns included temporary loss of visibility while still moving, deafness, toxic poisoning, etc. It has taken nearly seven years for the general public to become educated about air bags, how they work, and for what types of accidents they are and are not effective .

The typical reaction of customers to air bag performance (after a crash), is that they expect a deployment from all crashes. The classic comment is, "the bag malfunctioned, I was in a crash and it didn't deploy." The customers perception is that he "paid" for a safety device therefore it should work in every crash, regardless of the severity of the crash. Typically, when they are reminded that they were not injured indicating the minor severity of the crash, the possibility of minor abrasions as a result of a bag deployment, and reminded of the $1200+ air bag replacement cost, they are satisfied with the performance.

Many customers remark about smoke in the passenger compartment after a deployment. They believe the car must be on fire and become very alarmed. This "smoke" is largely made up of cornstarch bag lubricant and a small amount of dust coming from inflator propellant.

Often customers are unaware that a deployment has even occurred because the event happens so rapidly. They egress the vehicle immediately after it has come to a stop, and do not see the deployed bag lying in their lap. Upon returning to the vehicle and seeing the bag, they complain that the bag deployed after the crash and is therefore unsatisfactory and should be repaired under warranty.

> **Recommendation:** The public needs to be educated as to the programmed response of the AHS in both normal and abnormal situations as well as how to correctly interface with the AHS. This will increase the public's level of confidence in the system as well as prevent attempts to override correct system response.

Occasionally customer and/or dealer fraud is involved. There have been cases where the dealer or customer has complained of an inadvertent and partial air bag deployment where the bag is found just barely protruding from the steering hub vinyl cover. In these cases, the vehicle has been repaired without replacing the bag system with the bag merely stuffed back into its housing. These customer/dealer complaints are easily resolved when it is pointed out that there are several telltale signs present that indicate a full deployment did occur.

The SIR system has a recording feature that has been most useful to support legal claims investigations as well as maintenance. This system measures the velocity change from impact to deployment, duration of any diagnostic codes stored in memory, and warning lamp condition at the time of a crash. This recorder not only helps the mechanic to diagnose system or component failures, but has proved very helpful in discouraging customers and attorneys from initiating nuisance claims against the vehicle or component suppliers. This feature is relatively simple to add if the system is microprocessor based and supports sufficient memory space to allow such a recorder.

> **Recommendation:** An onboard recording device should be incorporated into the vehicle's AHS equipment in order to enhance diagnostics and discourage unfounded litigation.

The present customer demand for air bag installation in new vehicles has been greater in the short term than some vehicle manufacturers can meet. This demand may be attributed to at least three reasons. First, the general public is more concerned with their safety and well being than previously. Secondly, and this is partially the same as the first reason, an entire generation passed since the first tentative steps towards air bags were taken. During this time people, especially the younger buyers and users, have been educated by NHTSA, manufacturers, and driver training courses in the hazards of driving and the benefits of restraint systems in general. Thirdly, the air bag is seen as a much preferable passive restraint approach to the alternatives which preceded the air bag, such as passive seat and/or shoulder belts. These belts, whether mounted on the doors or moved into place by a "mouse" moving along the upper door frame, were widely recognized by the public and the popular automotive press as being inconvenient to use, not nearly as passive to use as intended, and even perceived as offering less protection than a simple manual seat and shoulder belt. Thus when some manufacturers offered air bags as the passive restraint system, the air bags were clearly seen by the buying public as a better alternative.

Risks

The public must be in agreement with the concept of AHS if it is to come to fruition. The cost of such a system is so high, its influence so extensive, that the taxpayer should understand the benefits, and want the system badly enough to be willing to support its cost. In fact initial public perception of new systems can sometimes be diametrically opposite to the eventual "correct" perception of a system. When Ford offered the "Life Guard" safety package in 1956, many consumers perceived this as an indication that Ford vehicles were less safe than other manufacturers vehicles and needed this additional package to make them as safe as other vehicles which did not offer such equipment.

Examples of government regulation not supported by the public are illustrated by the ignition - seat belt interlock installed on cars in 1975. That system failed miserably within a few months after introduction due to a lack of public support. Another decision turned around by public opinion occurred when the Mandatory Passive Restraint regulation was revoked. The IIHS filed suit on behalf of the public, against NHTSA, and won. That decision is in effect today making air bags one of the most popular new automotive features.

Task 3.3. Perform Tradeoff Analysis of Automobile Navigation Systems

Objective

The objective of this task is to present the experiences, results, and lessons learned during the development and field test of the TRAVTEK Advanced Driver Information System (ADIS). This study will review the scope of TRAVTEK and will contrast the experiences of that program with the challenges of AHS.

ADIS In The Market Place

An Automated Highway System will require a navigation, route planning, and driver information system. Navigation, route guidance, and services database systems are starting to appear on the market at this time. In addition, a number of large scale field tests of a variety of implementations of an ADIS have been conducted, both in the U.S. and abroad. The Europeans and the Japanese have been evaluating navigation and route guidance systems for the past several years. User response and acceptance of these systems has been generally favorable. Delco has recently developed an in-vehicle navigation, guidance and services database system that will be available for purchase in the near future. Rockwell International has recently introduced their “In vehicle navigation-route system” which will be available in the Oldsmobile-88 in June of 1994 at a cost of approximately $2000. Telephone dial-up services providing route selection, in some cases based on real-time traffic conditions, have been available for several years.

With the advent of these new technologies, drivers will be able to plan and drive trips with more assurance and ease. Drivers will be guided along a route by accurate and timely visual and voice messages rather than trying to read a map and drive at the same time. With the addition of mass transit data, drivers will be able to make travel decisions across a variety of transportation modes. Finally, drivers will receive real-time traffic information that will enable them to reduce travel time and fuel consumption and will improve safety while operating on the highway.

Introduction To TRAVTEK

Advanced Driver Information Systems (ADIS), such as TRAVTEK, provide assistance to the driver in location finding and navigation, destination finding, and route guidance. TRAVTEK was a demonstration project to develop and deploy a full function ADIS in a limited number of vehicles and to evaluate its use by a large number of drivers. The project was a cooperative venture between General Motors (GM), the American Automobile Association (AAA), and three levels of government transportation agencies: USDOT’s Federal Highway Administration (FHWA), Florida’s State Department of Transportation, and the City of Orlando. Each group funded their own effort, but cooperated effectively to build a highly integrated and complex system providing a complete set of ADIS features.

Work on the development of TRAVTEK began in 1989. At the end of 1991 GM shipped 100 fully equipped vehicles to Florida. At the same time, major infrastructure components were build in Orlando by the AAA and by the FHWA. The system was ready for field testing in March of 1992. In that month, the TRAVTEK team began a one year evaluation. Seventy-five of the cars were rented, by Avis to tourists visiting the Orlando area for generally one week periods. The other 25 cars were rented to local Orlando area residents for longer periods of time. Science Applications International Corporation (SAIC), under contract to the FHWA, conducted the evaluation and collected an enormous amount of data through in-vehicle recording, questionnaires and interviews, and measurements. SAIC reduced this data into a series of reports on each phase of the testing. These reports are scheduled for released by the FHWA in the fall of 1994.

Major Functions Of TRAVTEK

TRAVTEK provided the following ADIS features to the driver:

- An in-vehicle map display on a CRT showing the vehicle's location and a “street map” of the area surrounding the vehicle.
- In-vehicle navigation, using a combination of GPS, vehicle compass, dead reckoning and map matching to determine the vehicle’s location and heading.
- In-vehicle address location finding allowing the driver to locate on the map any location by street number and name.
- An in-vehicle “yellow pages” feature allowing the driver to find on the map businesses, attractions, and special events by type or name.
- An in-vehicle route finding feature to give the driver the quickest route to any selected destination.
- An in-vehicle route guidance feature to provide the driver turn-by-turn driving instructions to any chosen destination.
- A Traffic Management Center (TMC) to collect and provide real-time traffic incident and driving time information to the TRAVTEK equipped vehicles.
- A TRAVTEK Information and Services Center (TISC) to provide traveler information to the drivers via cellular telephone.

Technical Description

TRAVTEK consisted of three major components as illustrated in figure 1. These were the in-vehicle component together with two infrastructure components: the Traffic Management system (TMC) and the TRAVTEK Information and Services Center (TISC). The vehicles and the infrastructure were connected by a two-way radio system.

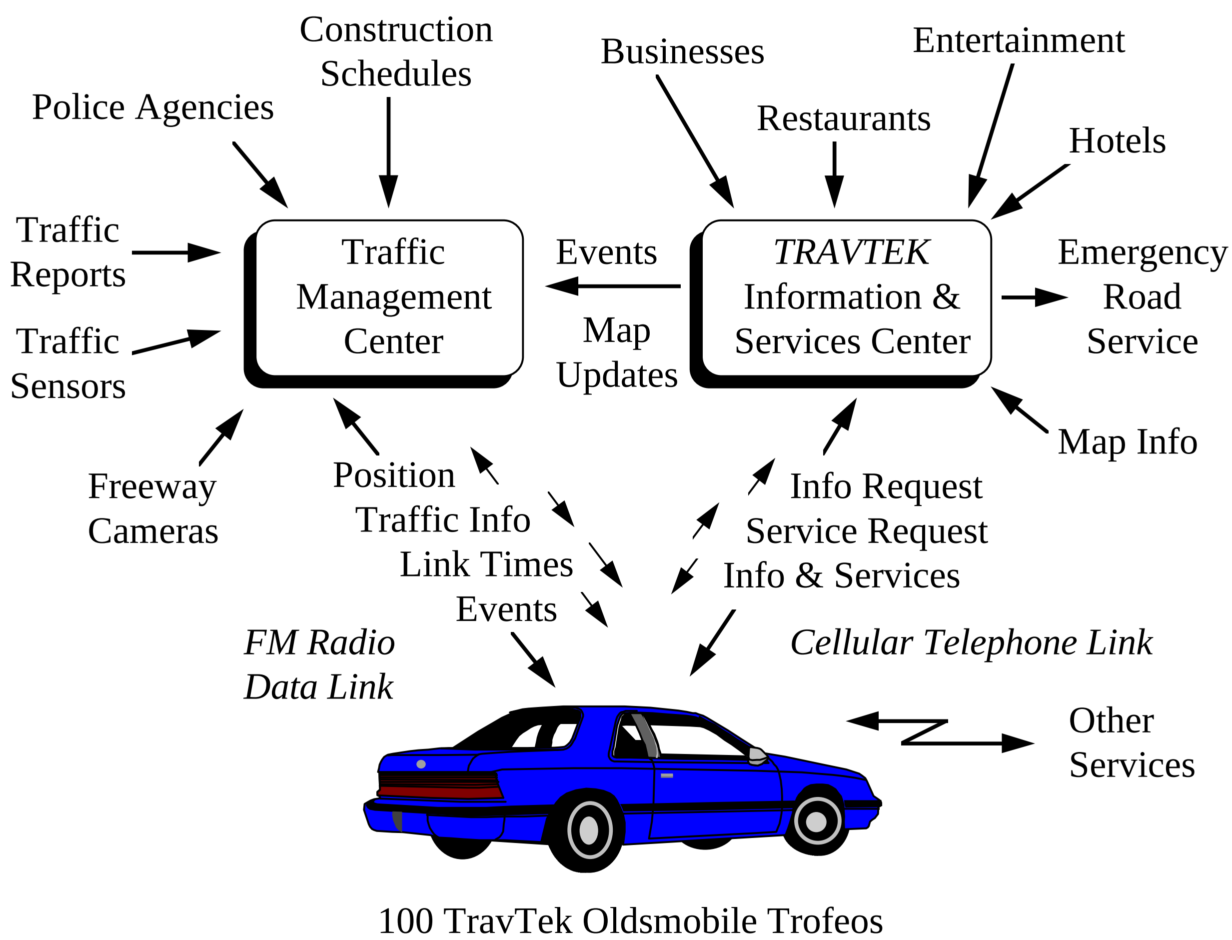

Figure 1. TRAVTEK System Architecture

The in-vehicle equipment, as shown in figure 2, consisted of two computers: one for route selection and guidance, and one for navigation, destination selection, and map display. The driver interface was through a 12.7 cm. diagonal color Cathode Ray Tube (CRT) display device (a part of the stock Oldsmobile Trafeo), touch keys on the CRT, and keys on the steering wheel. A voice message synthesizer was also included. Additional in-vehicle equipment included the two-way radio, a GPS receiver, and a cellular telephone. Map and "yellow pages" databases were stored in the vehicle on a hard disk. Real-time traffic information was received via the two-way radio.

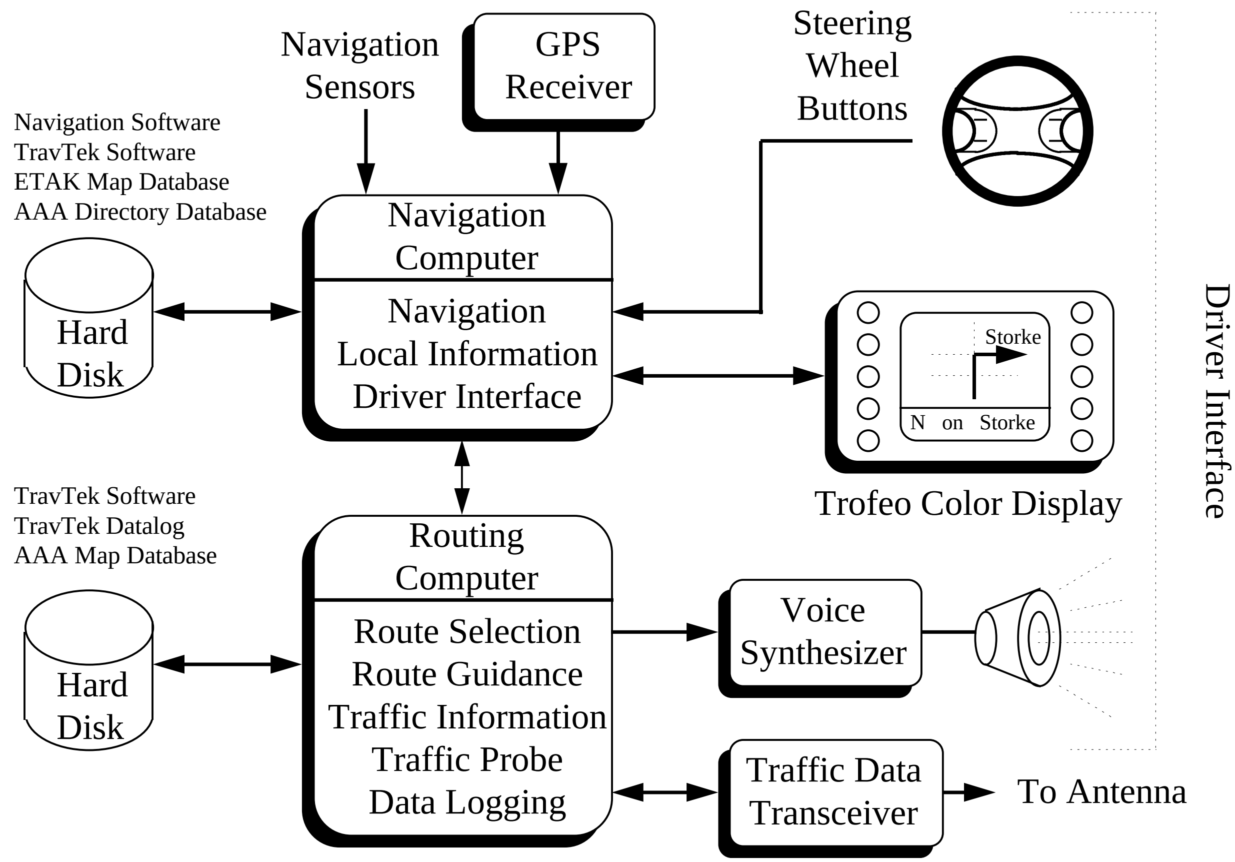

Figure 2. Example Of A Destination Selection Display

Software in the vehicle performed:

- Navigation – determining the vehicles position and heading.
- Map Display – a display on the CRT showing streets, the vehicle's present location, the destination, and the selected route to that destination.
- Destination Selection – by address or from a "yellow pages" of businesses and attractions.
- Route Selection – from current location to the selected destination for the shortest trip time based on current traffic conditions.
- Route Guidance – turn-by-turn driving instructions shown on the CRT and supplemented by voice messages.
- Traffic Data Reception – travel times and traffic incident data from the TMC.
- Traffic Data Reporting – minute by minute reports to the TMC on actual travel times as measured by the vehicle.

The TMC equipment consisted of workstations and communications equipment installed at the City of Orlando’s Traffic Operations Center. These computers gathered traffic information from a number of sources, including loops in the road, police departments, radio stations, a freeway surveillance system, and from the TRAVTEK vehicles themselves, fused this data into a common picture of current traffic conditions, and provided this information to the TRAVTEK vehicles via radio. Two classes of traffic information was transmitted to the vehicles: estimated travel time information for use in selecting the fastest route, and incident data to alert the driver to the existence of traffic accidents and dangerous situations. In return, the vehicles provided the TMC with current location and measured travel time information.

The TISC was operated by the AAA to provide supplemental help and information to the drivers of the TRAVTEK vehicles. Via a cellular telephone, the travelers could talk to operators at the TISC to obtain help in using the TRAVTEK in-vehicle equipment, to report problems, and to ask for additional tourist information not available through the TRAVTEK ADIS.

Features of the Driver Interface

Specific human factors criteria were applied to the design of the TRAVTEK system. It was critical that the display/control suite in the vehicle be designed such that the driver's capabilities were not exceeded and the primary task of driving the vehicle was not impeded. At the same time, one intent of an ADIS is to provide the driver with new information which will reduce the stress of driving.

The TRAVTEK had three driver interfaces: a visual display, keys for interacting with the computers, and voice message equipment to supplement the visual display with voice messages. Each vehicle had a 12.7 cm. diagonal color CRT mounted in the dash area on the right hand side of the driver (at about the center of the vehicle). For driver interaction, there were hard keys around the edge of the CRT, touchscreen controls on the CRT, and additional keys on the steering wheel. The touch keys were only active when the vehicle was in PARK and were used to select a destination and to obtain "yellow pages" information. When the vehicle was not in PARK, only a map or driving instructions were displayed and driver interaction was severely limited to turning on or off the voice messages with the steering wheel keys. Chimes were sounded to alert the driver to changing traffic situations and information. Synthesized voice provided the driver with supplemental route guidance information while driving.

As can be seen, every effort was made to limit driver interaction with the visual display when the vehicle was in motion. The touch keys were not active, only guidance information was displayed, and even those screens were highly optimized to provide the key information (type of turn, distance to turn, and name of street to turn onto) at a glance as shown in figure 3. In addition, guidance instructions were also available from voice message so that in most situations the driver never had to look at the screen while driving. The illustration of the screen in figure 3 is approximately full-size.

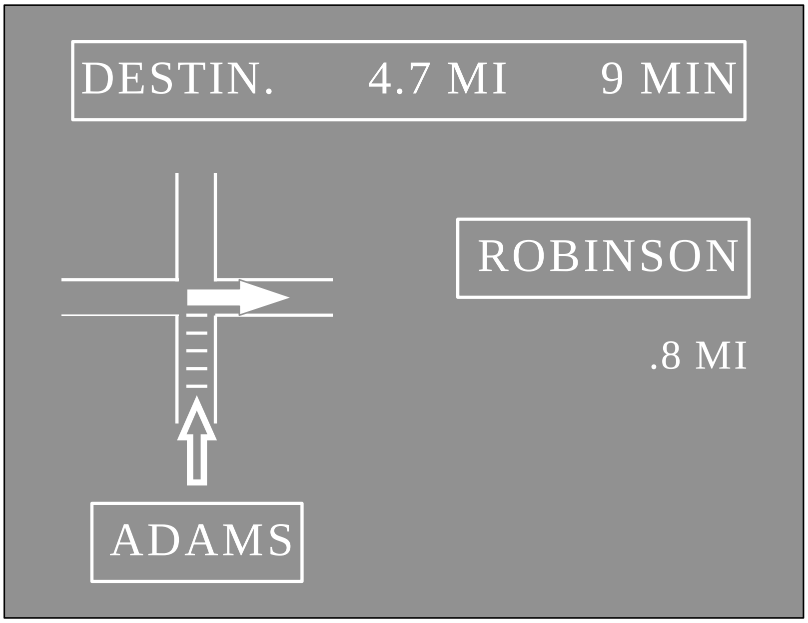

Figure 3. Example Of A Guidance Display

Prior to the conduct of the field tests, considerable human factors laboratory research was conducted to optimize the display/control suite in terms of ease of driver interaction. Map screens and display content attempted to provide basic information without cluttering and making display content complex. Considerations were also given to the ease of reading the displayed information (visual angle and font size) and to the use of color. Care was also taken to limiting the audio messages so that necessary information was presented without making the driver feel the system was chattering unnecessarily. Public acceptance of an ADIS is closely tied to the driver's comfort with using the driver interface and with common consensus that the driver interface is safe. Assessment of these issues was a significant part of the evaluation effort conducted for TRAVTEK.

TRAVTEK Field Tests

The TRAVTEK ADIS was evaluated in a year long field test conducted in Orlando, Florida from March 1992 through March 1993. General Motors provided 100 vehicles equipped with the TRAVTEK equipment. Seventy-five TRAVTEK vehicles were available to renters visiting the Orlando area, while the other 25 were used by local drivers.

During the one year operational field test period, TRAVTEK was subject to an elaborate and comprehensive set of evaluation studies. These were divided into three categories: user studies, driver performance studies, and system performance studies. The characteristics and content of the several studies are discussed in the following subsections.

User Studies

The user studies were "naturalistic" evaluations where various types of drivers were given free use of the vehicles for varying periods of time. Their use of the vehicles was evaluated through questionnaires, interviews, and data recorded in the vehicle. Two user studies were conducted:

- Rental Users Study – Over 2,500 visitors were rented a vehicle for periods ranging from 2 to 14 days.
- Local User Study – Over 50 Orlando residents were given use of a vehicle for up to 8 weeks.

Driver Performance Studies

The driver performance studies were highly controlled tests in which a small set of drivers were given very specific tasks to perform. Their performance was measured by questionnaires, interviews, data recorded in the vehicle, and by direct observation. Three driver performance studies were conducted:

- Yoked Driver Study – Tests in which usually 3 drivers were given vehicles, each with a different set of TRAVTEK features, and asked to perform the identical driving task so their performance could be directly compared.
- Orlando Test Network Study – Tests in which a variety of drivers (classified by age, gender, map reading ability, etc.) were given vehicles in a variety of configurations and asked to drive one of six pre-defined routes at different times of the day.
- Camera Car Study – Tests in a specially equipped vehicle in which video cameras were used to record eye movement data, use of vehicle controls, and the outside environment while the test subjects drove the vehicle.

System Performance Studies

The system performance studies analyzed the performance of the entire TRAVTEK system. These analyses included:

- Modeling Study – A traffic model was developed for the entire Orlando area so that impacts on traffic flow caused by TRAVTEK equipped vehicles could be estimated for varying degrees of market penetration. The model was used to assess the impact of an ADIS on travel times, congestion levels, accident rates, and vehicle emissions.
- Safety Study – Accident data, as well as driver performance data, was compared for the TRAVTEK vehicle and for non-TRAVTEK vehicles in equivalent driving conditions. An effort was made to relate ADIS features to increases or decreases in the expected rate of accidents.
- Architecture Evaluation – The effort studied the effectiveness of the infrastructure related performance features of the system, including its ability to accurately provide traffic data and the overall reliability of the system components.

- Global Evaluation – This study attempted to asses the macro level impact of the TRAVTEK on issues such as congestion reduction, economic benefit, safety enhancement, fuel consumption, and impact on the environment.

Driver Performance Studies

The objectives of these three field evaluations were: to: 1) determine the effect of alternative navigation guidance displays on safety related aspects of driver behavior, 2) provide the driver with up-dated traffic information to assess the impact on trip time savings and navigation efficiency, and 3) measure the effect of different display configurations on driver performance and navigation. Results obtained from the various test conditions were compared with a control condition that basically provided the driver with paper maps and the ability to communicate for directions. Data were obtained for different demographic groups and different levels of familiarity with the Orlando area.

Yoked Driver Study

In this field research study, three drivers in three separate TRAVTEK vehicles began driving from the same start point at approximately two minute intervals and drove to the same destination. The differences between the vehicles were the level of TRAVTEK features available to the drivers. One vehicle was equipped with complete navigation features (vehicle location, map display, route selection, and route guidance) plus real-time traffic information, the second vehicle had all navigation features without real-time traffic, and the third vehicle was a control where the driver was given a paper map. Driving trials were conducted daily for many days. A researcher rode along with the test driver and recorded time and data and would occasionally ask questions to assess driver workload.

The test drivers were visitors in the Orlando area and were recruited at the TRAVTEK exhibit located at Disney World. Prior to the test drives, drivers were given a series of skill assessment tests, including an acuity test, a contrast sensitivity test, an auditory recognition assessment, and three tests to assess map reading skill. Then each driver received approximately 50 minutes of training in the vehicles to become familiar with the TRAVTEK system, i. e., location of displays and controls and the interaction process. Drivers were then given hands-on training on how to program trip routes followed by six practice drives. Test drives occurred during the afternoon rush hour.

The objective of this study was to evaluate the contribution of real time traffic information to trip efficiency and to examine driver navigation performance under peak traffic conditions. Secondary objectives were to evaluate the TRAVTEK in-vehicle systems as they related to safety and driver workload, the relationships of system usability and utility to individual driver differences and to evaluate driver preference and perception of the TRAVTEK in-vehicle alternatives.

At specific points, the researcher riding with each driver prompted the driver for a subjective assessment of workload using a three point evaluation scale, “High, Moderate or Low". The drivers were asked to estimate their workload based on visual effort, time pressure, and psychological stress. Drivers were given examples of what might be considered low, moderate, or high workload in the pre-drive briefings. At the end of each test drive, drivers were asked to estimate the time it took to plan the trip and the time it took to make the total drive. At the completion of all of their test drives, drivers received a debriefing and were asked to fill out a questionnaire.

Orlando Test Network Study

The objective of this field test was to obtain driver performance and preference data for six different TRAVTEK navigation displays. The six navigation displays were:

- Guidance Display with Voice Guide.
- Guidance Display with no Voice Guide.
- Route Map with Voice Guide.
- Route Map with no Voice Guide.
- Voice Guide with no visual navigation display.
- Control condition, no electronic navigation display and no Voice Guide.

The Guidance Display is a schematic representation of the next turn and shows three items of specific interest to the driver: direction of turn, name of street to turn on to, and distance to turn. The Route Map is a standard paper map like display with the selected route highlighted. Voice Guide are voice messages of the turn instructions provided to the driver both before reaching the turning point and at the point of the turn.

Data collection (test drives) occurred at two different times of the day, i.e., half the drivers drove between 9:15 AM and noon, and the other half drove between 8:15 PM and midnight. Drivers were asked to drive one trip in each of the three visual configurations and were randomly assigned to the Voice Guide configurations. Procedures for testing, training, and practice drives were the same as the Yoked Study.

Camera Car Study

A specially equipped vehicle was used in the camera car study to obtain more detailed driver performance data than was available from the other two studies. Four video cameras were mounted in and on the test vehicle: one was focused on the drivers face and was used to obtain eye movement and glance data, a second camera provided a 60º field of view look through the forward windshield, a third camera was mounted behind the driver (over the shoulder look) and was used to record hand and foot interaction with vehicle controls, and the forth camera was mounted on the left-side rear view mirror to record location of lane markings relative to vehicle position as the vehicle was driven. Additionally, a computer recorded lateral and longitudinal control along with acceleration, vehicle speed and brake light status (on/off). Data was sampled 10 times per second.

The objectives of the camera data study (as differentiated from the other studies) were to:

- Assess driver performance as a function of age.
- Measure differences in driver performance as a function of experience using TRAVTEK.

Test drivers in the Camera Car Study were selected from three age groups, .i.e., young, between 16 and 18 years, middle, between 35 and 45 and older, 65 and older. The experience variable was measured by testing a group of 12 local Orlando drivers who were given use of a TRAVTEK equipped vehicle for two months. Their performance was measured on the first day they used the TRAVTEK vehicle and again after five weeks experience of driving the TRAVTEK vehicle. In addition, 18 visitors to the Orlando area participated in the camera car field test. Of these 18 drivers, six fell into each of the three age groups.

The primary goals of the camera car study were to:

- Provide data on the contribution of the TRAVTEK in-vehicle system to safety.
- Identify any safety hazards associated with the in-vehicle TRAVTEK system.
- Characterize changes in driver behavior as a function of experience in the use of in-vehicle systems.
- Analyze driver interactions with the in-vehicle systems that may aid in explaining findings from other TRAVTEK studies.

Preliminary Results of the Evaluations

TRAVTEK data collection was completed on March 31, 1993. Analysis of the volumes of data are continuing and final results will be released in the Fall of 1994. However, some preliminary findings have been released, primarily based on results from the user surveys and on data from the Driver Performance Studies.

The first set of preliminary results have been derived from the driver interviews, both of the user study drivers and the driver performance study drivers. The results across both groups were consistent. Drivers gave very positive responses when asked questions such as:

- Was the device easy to learn?
- Were the driving instructions easy to understand?
- Did the device help you find your way?
- Did the device help you pay more attention to your driving?
- Did the device help save time in reaching your destination?
- Could you easily read the text?
- Did you like the screen colors?

Drivers gave a generally negative response when asked questions such as:

- Was the screen distracting at night?
- Did the device interfere with your driving?

These responses reflect well on the care taken in the design of the interface between the driver and the in-vehicle computers.

A second set of preliminary results were developed from the recorded data taken in the vehicle. These results were not based on driver impressions but upon measures of how often the drivers used certain services and how their driving performance was affected. For instance:

- 70 percent of all trips were made using the navigation features. This was true both for visitors and for local drivers.
- Drivers used the Guidance Display about four times as often as the Route Map display. This however, indicates the importance of alternative display configurations for a significant number of drivers.
- By a factor of 20:1, drivers used the Voice Guide feature. This indicates a strong preference for not wanting to glance away from the road.
- Drivers were able to reduce their trip planning time by a factor of about three with the automated destination finding and route selection features.
- Drivers were able to reduce travel time by a factor of about 20 percent when using the route guidance features.

Among other conclusions, these results indicated that automation aids help in efficiency of driving and that drivers prefer voice input devices which do not require them to glance away from the road.

Relationship With AHS

In AHS, where the driver will come under automated control, the driver will be required to select and/or provide information regarding his destination. The driver, prior to system check-in, will input information regarding the trip he is undertaking. The types of driver interaction with the system will include: entering departure and destination points, requests for the best route based on distance or travel time, and etc. Additionally, the driver should receive information regarding trip progress, deviations from his selected or planned route, and his status and location within the AHS.

A system with some of the features of TRAVTEK will be incorporated into AHS. The ability for the driver to receive navigation and traffic information, route planning and services information (“yellow pages”), vehicle status within the AHS, platoon information, and exiting information would be desirable for several reasons that are psychological, relate to alertness, and can reduce stress and workload. Once under automated control (and different from TRAVTEK field tests), the driver would need to interact with the system in terms of requesting and receiving information, trip status, and inputting requests for possible destination changes.

Apart from the overlap of some driver functions between an ADIS and an AHS, as a collaboration between public and private interests TRAVTEK offers some useful "lessons learned" for a similar collaboration on AHS. Finally, the extent and importance attached to the TRAVTEK User Evaluation plan, and the unfortunately late recognition of its importance, can provide a useful reference for an AHS development effort.

Requirement Comparison

Interaction

Both TRAVTEK and an AHS have as an important facet an interaction with the driver. Obviously, for the portions of an AHS where the vehicle is under automatic control, the nature of the interaction with the driver is to convince them that it is safe and desirable to be out of the driving loop. This phase of the AHS experience has no counterpart in TRAVTEK. On the other hand, driver interaction both before and after the automated phase of an AHS trip have a lot in common with TRAVTEK. The design guidelines that were followed for TRAVTEK are completely applicable to an AHS for test driving tasks. In particular, the task of destination selection, the need to not interfere with driving task during the check-in activities prior to assuming fully automatic control of the vehicle, the need to alert the driver when the vehicle is about to be released from automatic control, and the need to not interfere with the driver while exiting the AHS highway are all driver activities to which the TRAVTEK experiences are directly applicable. Major "lessons learned" from TRAVTEK include:

- Trained human factors specialists should participate in designing the driver interface. Personnel with the proper background know and can apply the basics of human/computer interaction research. Use of the appropriate size font based on standard visual acuity is one of these basics which is commonly overlooked. Avoiding overuse of color or voice messages are others. Design of consistent displays and menus where information are tasks are the same from screen to screen is yet another.

- The design should be ensured to be suitable to the wide range of people who drive, and almost anyone, from any walk of life, drives. For instance, nomenclature testing was done on TRAVTEK to avoid the use of computer terminology with which many people are not familiar. In addition, the tasks should be designed to be almost intuitive since driver training is so uncertain.

- The addition of any task which may distract the driver from safely driving the vehicle should be carefully considered. That task should be designed to create the minimum distraction from primary driving tasks. The entire driver task load during check-in and check-out should be considered. Testing should also be performed, similar to the camera car testing of TRAVTEK, to evaluate the impacts of the design. In general, guidelines should be developed and applied which restrict the use of displays and controls during driving, reducing the density of visually presented information, and use of auditory tones to augment the visual displays.

- The system response time should be designed to meet user expectations. One of the most difficult, and therefore most often ignored, design tasks is to design acceptable response times into a system. These need to be established at the beginning of the design process and then rigorously enforced as the design is implemented.

    Recommendation: **S**ound Human Factors principles should be used when designing the driver interface to ensure that the added tasks do not interfere with the primary driving task.

Complexity

Although very complex by previous automotive standards, TRAVTEK did not have the complexity of an AHS. TRAVTEK was also far less dependent on the infrastructure. And of course, TRAVTEK was only a driving aid, so its failure was not safety critical. However, TRAVTEK was a complex enough system to serve as a case study for the depth of systems engineering techniques which should be applied to complex systems design, and which will even be more important in the design of the AHS. These include:

- Establish clear, comprehensive, documented, and testable requirements at the beginning of the program and then subject them to a controlled review and change process for the life of the program. On TRAVTEK, this was not done for the Traffic Management Center. As a result, it never supported the system as expected.

- Ensure that functional testing is sufficiently funded to be complete and rigorous. On TRAVTEK this activity was under-funded and skipped because of schedule constraints. The evaluation effort could only assume the underlying system was working, and in some cases it was not.

- Place importance on defining and documenting subsystem interfaces, especially those between different suppliers.

    Recommendation: System Engineering principles should be applied which focus on establishing clear and sufficient system requirements up front and rigorous system level performance testing at the end.

Safety

For reasons described above, TRAVTEK was never intended to be safety critical in the way that an AHS will be. However, care was taken in the design of TRAVTEK to prevent it from becoming a safety liability by distracting the driver from the primary driving task. This concern will exist for AHS too, as long as the driver is in control of the vehicle. The techniques important in overcoming this safety risk were discussed above under the paragraph on Interaction.

Reliability

Because of the lack of a tie to a safety requirements, the approach taken on TRAVTEK with respect to reliability was to make the subsystems out of good quality commercially available components and accept the resulting system reliability. Certainly, no redundancy or automatic fault recovery features were included in the design. Obviously, the same approach will not be sufficient for an AHS where fail-safe is an absolute requirement. However, use of reliable components and fault recovery processes is only part of the effort needed to achieve acceptable levels of system reliability. The system should also alert operators and maintenance personnel to the existence of a failure and the need for repair. TRAVTEK fell short in this area and is a good example of the cost of such an oversight. For instance, it was not easy to determine from the vehicle that a radio failure had occurred. Most drivers were not trained to detect the difference. As a result, some experimental data was found to be invalid and unusable because of an undetected radio failure in the vehicle. This illustrated the importance of designing aids into a system to help the operators quickly detect component failures.

> **Recommendation:** System requirements should include diagnostics to alert operators of failed components.

Environment

As noted in other Comparable Systems Analyses, the automotive environment is one of the harshest in the world for electronic equipment. For TRAVTEK, the team that designed the in-vehicle equipment had many years of experience in automotive electronics design and were completely familiar with the unique temperature extremes, the electromagnetic interference, the vibration and shock, unstable power source, etc. that exist within the vehicle. If TRAVTEK offers any “lesson learned” in this area it is that the people designing the in-vehicle AHS equipment should also have the same depth of experience in automotive electronic design for the project to succeed.

Numerous Diverse Subsystems

The correlation between an ADIS and an AHS, both for the vehicle and for the infrastructure, is very close for this factor. Both contain computing elements, communications elements, displays and operator input elements, data storage elements, and very complex software. About the only significant difference is in the fault recovery elements which an AHS must have but which TRAVTEK did not. To integrate these numerous diverse subsystems into a smoothly functioning system requires a system engineering team with a system engineering methodology. This was true for TRAVTEK and will be even more true for an AHS. The components of such a systems engineering approach are many and some have been mentioned before: clear and complete system requirements, documentation through which the flowdown of these requirements can be traced, a well controlled change process (configuration management), specialty engineering input (human factors, safety, etc.), sound software engineering practices, a thorough and independent test and validation effort, and attention to maintenance and operational needs. TRAVTEK did have such a system engineering oriented team, at various levels, and the numerous diverse subsystems that made up both the vehicle and the infrastructure did come together as an operational system. The system engineering challenges for an AHS are much greater and that same systems engineering oriented team must likewise be in place.

Operation Over a Geographically Wide Area

The primary issue here, operation of an AHS in all extremes of weather, was not an issue for TRAVTEK. Since no vehicle control modes existed on TRAVTEK, weather, by and large, was not an issue. However, there is one geographically related issue where an ADIS and an AHS do intersect, and that is the geographic database the driver will use to indicate desired destinations. With AHS, a driver would specify a destination and the AHS would select the best route through the available network of automated highways so that the driver has the shortest distance to drive after exiting the automated highway. Obviously, a database is needed in which destinations can be easily found, using a variety of techniques, and from which a route can be extracted using both automated and non-automated highways. As an ADIS, TRAVTEK developed the map and attraction database requirements, methods for selecting destinations from this database, route selection logic, and even route guidance logic, all of which will be applicable to anything but the most simple AHS. TRAVTEK also was unable to adequately address a problem which will become acute when inter-city automated highways go into service. TRAVTEK covered an area of about 3000 square kilometers in metropolitan Orlando but treated the entire area as one large city. In entering addresses, the driver could not specify a city. Sometimes this would result in a common address (e. g., 100 north Main) being found in several cities. The driver would then be given a list of cities with that address and expected to select the one of interest, without being given any information at all as to the location of that city. The basis of the problem was that it was difficult to represent an area (like a city) on the TRAVTEK CRT display. Makers of paper maps have developed several ways to show city locations but these are not readily transferable to a computer monitor. It is expected however, that ADIS’s will proliferate before AHS’s and that acceptable techniques to resolve this problem will be developed.

Another issue of concern with respect to the ability to operate over a wide geographic area is the problem of vehicle-to-infrastructure communications. TRAVTEK, used an 800 MHz frequency pair which covered most of the area of the map database and all of the area for which real-time traffic data was generated. But it was not an expandable solution. It would not work if hundreds of thousands of vehicles were involved instead of just 100. The TRAVTEK communications solution was project specific. The funding necessary to develop a prototype solution was simply not available. Prototype solutions are being addressed in other, on-going, FHWA ITS studies. Obviously, the question of a prototype vehicle-to-vehicle and vehicle-to-infrastructure communications solution should be addressed in an AHS prototype development. However, it is likely that the optimum solution for an AHS will not be the optimum solution for an ADIS.

Recommendation: Various features of an AHS are the same as features for other ITS systems. Communications and the driver interface are just two. Standards for AHS should be compatible with those for ITS in general.

Failure Modes and Outage Constraints

There is a low correlation for these performance factors between an ADIS and an AHS. Although the failure modes of electronic equipment will be similar, an AHS will contain mechanical components which have no analog in an ADIS. Furthermore, the consequence of a failure is drastically different. Therefore, an ADIS offers no useful guidance in this area. The study of other comparable systems, like airplane controls and automatic train controls, will offer very useful guidance.

Lessons Learned

It is possible to distill from TRAVTEK a series of lessons learned. Things that worked well and which should be repeated during the AHS development and implementation as well as mistakes that were made on TRAVTEK and which should be avoided on AHS. The involved issues are divided into two categories: the development and evaluation phase (including both technical and management issues) and issues relating to introduction or deployment of mature products and systems.

Programmatic And Developmental Issues

TRAVTEK was primarily, almost solely, a development and evaluation project. Its purpose was to demonstrate the feasibility of an ADIS by building a fairly complete system and to evaluate its acceptance by having a broad sampling of drivers use it. The following are the most significant “lessons learned”:

- Management philosophy. TRAVTEK operated under a “manage by consensus” style. Almost all important issues were discussed in open meetings with all project stakeholders present and able to express their concerns and position. After such open discussions, it was always possible to agree to a course of action which everyone agreed was the best possible under the circumstances. This approach was facilitated in three ways. First there was a very natural division of responsibility between the partners which greatly lessened the impact of one partner on the work of another. Second, the responsibilities of each partner (with a major exception mentioned below) were established in some detail at the very beginning of the effort. Third, and finally, the project held meetings every six weeks for the entire length of the effort at which all partners were present. In addition, careful minutes were kept in which all actions items were noted and assigned to a specific individual. This kept the dialogue between the partners going and insured that critical items were not forgotten but regularly discussed until they could satisfactorily be resolved.

Recommendation: Program Management should emphasize the building of consensus.

- Importance of a Statement of Work and clear funding responsibilities. On TRAVTEK, each major partner (General Motors, the American Automobile Association, and the Public Sector) funded their own effort. There was no prime contractor but three equal and independent partners. In addition, each partner had responsibility for clearly separate and relatively independent parts of the system. This made preparation of a Statement of Work easy and ensured that the funding responsibilities were usually obvious. This natural division of responsibilities greatly contributed to the smooth running of the project. To illustrate its importance, it is only necessary to consider the one aspect of the project where responsibilities were not clearly defined in the beginning and the problems that caused. At the start of TRAVTEK the scope of the evaluation effort was not well defined and the funding responsibility was not established. It was over a year before these problems were resolved. As a result, features in the vehicle and the infrastructure were late in being defined, work started late on the software package to manipulate the vast amount of recorded data, and efforts of the partners to support the evaluation tasks always were underfunded and behind schedule.

    Recommendation: A well thought-out Statement of Work for all participants and all activities, accompanied by adequate funding, should be the first order of business.

- Configuration Control. Development of TRAVTEK continued throughout the evaluation phase. Software fixes were installed, design deficiencies were corrected, and of course, errors in the map database were corrected. It was found necessary to implement strict configuration control procedures so the evaluation team knew the configuration, and the characteristics, of the system being tested. Even at that, it proved difficult in some instances to usefully compare data recorded at the beginning of the evaluation period with data recorded at the end. These types of incremental changes are inevitable over a long evaluation period, so the best that can be done is to ensure the evaluators know how and when the system changed.

- Performance Issues. In some aspect, it proved very difficult to establish measurable performance parameters for parts of TRAVTEK. For instance, a measurable parameter was never established for how good traffic data from the Traffic Management Center had to be. It turned out that the poor quality of this traffic data was the most serious performance flaw in TRAVTEK. Local users, familiar with Orlando traffic, preferred not to receive the TMC data. The lesson here is that performance parameters should be established and tested for all parts of the system. If this had been done for the TRAVTEK TMC it may not have solved the quality problem, but certainly would have focused more attention to the problem.

    Recommendation: A comprehensive set of performance parameters along with reasonable evaluation methods should be established.

- Interface Definition. Since the division of responsibilities on TRAVTEK followed natural system boundaries, this made the preparation of a detailed and complete interface specification relatively easy. The fact that this detail was documented and available to both responsible partners certainly contributed to the interoperability of the system components.

Recommendation: Divide the work among the participants so that simple and easy to define interfaces exist between their efforts.

- Shakedown Period. Because of funding problems, different completion dates of the system components, and schedule pressure to begin the evaluation phase, a rigorous functions testing of the completed TRAVTEK system was never accomplished. Although subsystem testing by the responsible partners did uncover most problems, some critical issues only came to light after the evaluation started.. This led to more changes during the evaluation than were necessary and the loss of valuable time from the evaluation effort.

  Recommendation: Do not shortcut the functional and performance testing effort.

- Inter-jurisdictional Conflicts. By and large, the project was rewarded with extremely good and productive cooperation between the three public sector agencies: the Federal Highway Administration, the Florida Department of Transportation, and the City of Orlando. The interests and abilities of these agencies meshed very well. However, the project found it difficult to obtain effective support from most other local agencies. The plan was to receive traffic incident data from other local police departments, and some even were provided terminals to enter this data. But little support, or data, was received, in part because these agencies were given nothing (neither traffic data nor recognition) in return. Achieving support from minor players, either public or private, is very difficult and requires careful and sensitive planning.

- Public Disclosure. TRAVTEK had and overcame a potential problem with premature disclosure of some project data. Since the two private partners were funding their own effort, they wanted to keep test and evaluation data out of the hands of competitors. This concerned the raw evaluation data and not the carefully analyzed results of the evaluation contractor. The problem arose because various public agencies, and to some extent private contractors being funded with public money, had legal requirements that might have led to disclosure of the data. The problem was resolved by ensuring that the raw data stayed in the possession of the concerned private partner. Only carefully extracted subsets were provided to the evaluation contracts. Of course, the evaluation contractor had complete visibility as to the types of data available to ensure they received everything they needed.

- Informed Consent. Ethical concerns about ensuring that test subjects understood the nature of the tests and their actions were being recorded for later analysis were overcome by having each subject sign an informed consent document.

- Privacy. TRAVTEK was implemented such that is was possible to identify specific vehicles and to track the route of any vehicle. To ensure the anonymity of the assigned driver of any vehicle, all information as to the specific identity of the driver was impounded by either the AAA or the rental car agency and not released to the other partners or to the evaluation contractor.

Introduction Related

The scope of the TRAVTEK effort did not include development of possible deployment scenarios or, with the exception of some analysis on “willingness to pay”, any of the issues of deployment. For the most part it was only a feasibility demonstration and benefits analysis. As a result, such intriguing questions as “which should come first the in-vehicle equipment or the infrastructure?” and “how do you establish a communications standard?” were not addressed. However, these questions are under study in later FHWA projects now underway. Certain deployment related questions did come up during the development of TRAVTEK, and two of the larger issues concerned product liability and the availability of map databases.

- Product Liability. Concern about potential product liability was the basis of many technical discussions of proposed design features. It was, of course, an important issue in designing the driver interface and was a factor is such decisions as prohibiting any interactive display when the vehicle was not in park, not allowing use of the touch screen when the vehicle was in motion, the design of a simple guidance screen, and the use of voice messages to supplement visual displays. Product liability was also a concern to the AAA and led them to extraordinary efforts to improve the quality of the map database. But there also was a dark side to what sometimes was a preoccupation with product liability concerns. Occasionally, instead of stimulating the design of the highest quality product, it resulted in the fearful deletion of a desirable feature. Management should ensure that when a desirable feature is identified, product liability concerns can be met by building higher quality into the product.

  Recommendation: Channel product liability concerns into increased product quality.

- Availability of Map Databases. In 1989, at the start of TRAVTEK, the team discovered that a map database of Orlando, suitable for route selection, was not in existence. Electronic map database, either in existence or being developed, for generating paper maps were not sufficient. The complexity of freeway interchanges, complete identification of one-way streets, and the inclusion of turn restrictions were just some examples of the more detailed information that was needed for route selection. Existing “yellow pages” databases of services and attractions, as used for tour books and telephone books, were also not sufficient. These were both incomplete and out-of-date. The TRAVTEK partners spent considerable effort to develop sufficient databases in both of these areas. However, since 1989, the commercial introduction of various products based on these types of electronics databases has spurred their development. The availability of such databases to support an AHS should not be a problem.

Risks

The major risks of an AHS will be public concern over price, benefits, and safety. The risk of public acceptance of an ADIS like TRAVTEK were largely limited to only one of these, price. The TRAVTEK evaluation showed that driver liked and would use the features and that the system was not a safety hazard as implemented. But people's expectation of a reasonable price for the perceived benefit were never in line with the cost of building such devices, even just the in-vehicle device. However, the relative cost of electronic computing, storage, and display devices continue to fall. Commercial, feature sparse, vehicle navigation products are now appearing on the market. It is reasonable that the price/cost curve will soon intersect and TRAVTEK like products will become available. An AHS demonstration project should be able to resolve the safety risk. Finding a way to overcome the benefit risk will be an interesting challenge.

CONCLUSIONS

The experience gained from the three comparable systems, BART, SIR, and TRAVTEK, offer a number of important insights into the application of new technologies to the field of passenger transportation. These lessons reflect the process of technology development and management that may also be experienced in the development of an automated highway system.

On the technical side, these systems offered additional insight into appropriate techniques for technical systems specification, verification of system performance, initial pre-deployment testing, and quality assurance. Given the potential high complexity of the many systems involved in AHS, successful deployment depends critically on the ability to specify and test a highly reliable system. A related issue is the treatment of both system safety and reliability in the technical development and in system operation. In addition, the level of effort required to maintain the automatic systems is an important consideration. Specific recommendations from the technical side include the following.

Technical systems specifications:

- A complete AHS system requirements specification is necessary at the beginning of the development process. This specification should be the focus of strong scrutiny in order to avoid creating an unnecessarily complex system. Clear, comprehensive, documented, and testable requirements should be established at the beginning of the program and then subject them to a controlled review and change process for the life of the program.

- Trained human factors specialists should be utilized in the design of the driver interface. Personnel with the proper background know and can apply the basics of human/computer interaction research. It should also be ensured that the design is suitable to the wide range of people who drive. For instance, nomenclature testing was done on TRAVTEK to avoid the use of computer terminology with which many people are not familiar. In addition, the tasks should be designed to be almost intuitive to minimize driver training requirements. The entire driver task load during check-in and check-out should be considered. The addition of any task which may distract the driver from safely driving the vehicle should be carefully considered. That task should be designed to create the minimum distraction from primary driving tasks. In general, guidelines should be developed and applied which restrict the use of displays and controls during driving, reducing the density of visually presented information, and use of auditory tones to augment the visual displays. One of the most difficult, and therefore most often ignored, design tasks is to design acceptable response times into a system. These need to be established at the beginning of the design process and then rigorously enforced as the design is implemented.

- Importance should be placed on defining and documenting subsystem interfaces, especially those between different suppliers. Various features of an AHS are the same as features for other ITS areas. Communications and the driver interface are just two. Standards for AHS should be compatible with those for ITS in general. Since the division of responsibilities on TRAVTEK followed natural system boundaries, this made the preparation of a detailed and complete interface specification relatively easy. The fact that this detail was documented and available to both responsible partners certainly contributed to the interoperability of the system components. Division of the work among the participants should be such that simple and easy to define interfaces exist between their efforts.

Verification of system performance:

- A comprehensive set of performance parameters along with reasonable evaluation methods should be established. In some aspect, it proved very difficult to establish measurable performance parameters for parts of TRAVTEK. For instance, a measurable parameter was never established for the quality of traffic data from the Traffic Management Center. It turned out that the poor quality of this traffic data was the most serious performance flaw in TRAVTEK. Local users, familiar with Orlando traffic, preferred not to receive the TMC data. The lesson here is that performance parameters should be established and tested for all parts of the system.

- In the development and procurement of AHS technologies, a competent and independent technical review team should be retained in each phase of the technical development and testing of the system.

Initial pre-deployment testing:

- Functional testing should be sufficiently funded to be complete and rigorous. On TRAVTEK this activity was under-funded and skipped because of schedule constraints. The evaluation effort could only assume the underlying system was working. Because of funding problems, different completion dates of the system components, and schedule pressure to begin the evaluation phase, a rigorous functions testing of the completed TRAVTEK system was never accomplished. Although subsystem testing by the responsible partners did uncover most problems, some critical issues only came to light after the evaluation started. This led to more changes during the evaluation than were necessary and the loss of valuable time from the evaluation effort.

- The highest priority should be given to safety and reliability in pre-service testing. Safety issues should be given highest priority in determining the readiness of an AHS system before start of service. Systems which have an overriding impact on safety obviously require extensive testing. It should also be realized that the formulation of test procedures, standards, and specialized instrumentation requires long lead times which can be comparable to the system development time.

- Test and evaluation procedures should be a mix of actual testing and simulation to span all possible response scenarios.

Provide quality assurance:

- Sufficient time in the AHS development process should be left for product testing and quality control. This involves allowing ample time for suppliers to debug new technical sub-systems, as well as time and resources to test and debug the fully-integrated AHS on site before beginning operation. Development of TRAVTEK continued throughout the evaluation phase. Software fixes were installed, design deficiencies were corrected, and of course, errors in the map database were corrected. It was found necessary to implement strict configuration control procedures so the evaluation team knew the configuration and the characteristics of the system being tested. Even at that, it proved difficult in some instances to usefully compare data recorded at the beginning of the evaluation period with data recorded at the end.

System safety:

- AHS development should include both safety and systems engineering functions from the earliest part of system planning, design and development. AHS specifications and standards should carefully balance the needs for technical innovation with the need for more specific design criteria to assure a safe and reliable system.

Reliability:

- System requirements should include diagnostics to alert operators of failed components. AHS specifications should include a strong emphasis on the design issues associated with service degradation, including equipment malfunctions in the vehicle, at the wayside, and in the infrastructure. In addition, these systems should be sensitive to the information provided to drivers during automatic operation and especially during degraded service conditions. Human factors research should emphasize the driver's response to information especially in degraded service or emergency situations.

Maintenance:

- Maintenance issues should also be included early in the planning stages for an AHS, focusing on long-term maintenance requirements. For both vehicle- and infrastructure-based components, these requirements include maintenance equipment to identify and repair failures, common information systems, and clearly-defined procedures for addressing scheduled and unscheduled maintenance needs.

Non-technical issues included such areas as the continued political pressure to bring the system such as BART into revenue service, coupled with the early loss of public confidence. Typically, new technologies in transportation come under intense political pressure, as elected officials press for early photo opportunities and quick benefits to improve their political standing. The high expectations already placed on AHS ensure that the political process will have much bearing on the development and deployment of these systems. Furthermore, in considering the early stages of AHS deployment, safeguards are necessary to avoid quick loss of public confidence. Close scrutiny of AHS operations is unavoidable, but lessons from the three comparable systems may help avoid the erosion of public trust that may seriously hamper planned AHS projects. Specific non-technical recommendations include the following.

To minimize political pressure:

- Technical personnel should maintain high visibility in AHS decision-making throughout the development process. Administrative and management boards should include staff with a high degree of technical competence in AHS.

- As much as system design will allow, AHS projects should take advantage of incremental deployment. This may imply that an automated highway be deployed in a small corridor initially, allowing for system expansion to other corridors in the near future. The selection of an initial corridor should be based at least in part on the ability of that corridor to demonstrate significant first user benefits. The development of AHS systems will likely follow the trends of automotive systems such as the air bag with respect to the driving developmental influences, which are:

  * First generation systems are driven by the need to provide features which are pleasing to the customer, incorporate desirable technical, diagnostic, and service functions, meet overall cost targets, and meet applicable legislative requirements.
  * Second generation systems continue to meet the first generation requirements while also placing increased emphasis of cost and packaging considerations (size, shape, weight, and location).
  * Third generation systems meet all earlier generation requirements while also meeting the need to integrate functions both within the system and with other systems and addressing concerns for the recycleability of system components.

To increase public confidence:

- The introduction of a pervasive consumer oriented system such as AHS needs the highest degree of coordination between government, manufacturers, consumer needs/wants, and technical state-of-the-art. The public perception of the use, benefits, and operation of a system is fundamental to market place acceptance.

- The public needs to be educated as to the programmed response of the AHS in both normal and abnormal situations as well as how to correctly interface with the AHS. This will increase the public's level of confidence in the system as well as prevent attempts to override correct system response.

Management/funding philosophy:

- TRAVTEK operated under a “manage by consensus” style. Almost all important issues were discussed in open meetings with all project stakeholders present and able to express their concerns and position. After such open discussions, it was always possible to agree to a course of action which everyone agreed was the best possible under the circumstances. This approach was facilitated in three ways. First there was a very natural division of responsibility between the partners which greatly lessened the impact of one partner on the work of another. Second, the responsibilities of each partner were established in some detail at the very beginning of the effort. Third, and finally, the project held meetings every six weeks for the entire length of the effort at which all partners were present. In addition, careful minutes were kept in which all actions items were noted and assigned to a specific individual. This kept the dialogue between the partners going and insured that critical items were not forgotten but regularly discussed until they could satisfactorily be resolved. Program management should emphasize the building of consensus. Achieving support from local agencies, either public or private, is very difficult and requires careful and sensitive planning.

- AHS development should include an aggressive and honest public information effort. This should include open public forums to discuss system planning and development and, as much as politically feasible, candid discussion of problems with development and deployment.

- On TRAVTEK, each major partner (General Motors, the American Automobile Association, and the Public Sector) funded their own effort. There was no prime contractor but three equal and independent partners. In addition, each partner had responsibility for clearly separate and relatively independent parts of the system. This made preparation of a Statement of Work easy and ensured that the funding responsibilities were usually obvious. This natural division of responsibilities greatly contributed to the smooth running of the project. A well thought-out Statement of Work for all participants and all activities, accompanied by adequate funding, should be the first order of business.

Privacy issue:

- TRAVTEK overcame a potential problem with premature disclosure of some project data. Since the two private partners were funding their own effort, they wanted to keep test and evaluation data out of the hands of competitors. This concerned the raw evaluation data and not the carefully analyzed results of the evaluation contractor. The problem arose because various public agencies, and to some extent private contractors being funded with public money, had legal requirements that might have led to disclosure of the data. The problem was resolved by ensuring that the raw data stayed in the possession of the concerned private partner. Only carefully extracted subsets were provided to the evaluation contracts. Of course, the evaluation contractor had complete visibility as to the types of data available to ensure they received everything they needed.

- Ethical concerns about ensuring that test subjects understood the nature of the tests and their actions were being recorded for later analysis were overcome by having each subject sign an informed consent document.

- TRAVTEK was implemented such that is was possible to identify specific vehicles and to track the route of any vehicle. To ensure the anonymity of the assigned driver of any vehicle, all information as to the specific identity of the driver was impounded by either the AAA or the rental car agency and not released to the other partners or to the evaluation contractor. For AHS, individual privacy should be considered in such areas as check-in/check-out, route planning and toll collection.

To mitigate liability concerns:

- Concern about potential product liability was the basis of many technical discussions of proposed design features for TRAVTEK. It was, of course, an important issue in designing the driver interface. Product liability was also a concern to the AAA and led them to extraordinary efforts to improve the quality of the map database. But there also was a dark side to what sometimes was a preoccupation with product liability concerns. Occasionally, instead of stimulating the design of the highest quality product, it resulted in the fearful deletion of a desirable feature. Management should ensure that when a desirable feature is identified, product liability concerns can be met by building higher quality into the product.

- A liability budget should be firmly established early in the AHS development process. A manufacturer needs to clearly understand its liability exposure in able to properly budget the cost of liability into the AHS system's business case.

- An onboard recording device should be incorporated into the vehicle’s AHS equipment in order to enhance diagnostics and discourage unfounded litigation.

In light of the preceding issues, the major risk for an AHS will be the public concern over price, benefit, and safety. Drivers may like the features of the system and would utilize it if perceived as safe. An AHS demonstration project should be able to resolve the safety risk. However, people’s expectations of a reasonable cost should be consistent with the anticipated benefits. Finding a way to overcome the benefit risk will be an interesting challenge which will hopefully be aided by the lessons learned from comparable systems.

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