Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Comparative Systems Analysis: Comparing Automated Highway Systems to air Traffic Management

U.S. Department of Transportation
Federal Highway Administration

Publication No. FHWA-RD-94-187
November 1995

FOREWORD

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

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

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

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

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

NOTICE

TABLE OF CONTENTS

TABLE OF CONTENTS (concluded)

LIST OF FIGURES

LIST OF ACRONYMS

AAR	Airport Acceptance Rate
ACARS	Aircraft Communications Addressing and Reporting System
AHS	Automated Highways System
ARINC	Aeronautical Radio Inc.
ARS	Accident Reporting System
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATCSCC	ATC System Command Center
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ASR	Airport Surveillance Radar
CAT	Category
CNS	Communication, Navigation, Surveillance
CRM	Collision Risk Model
CTAS	Center/TRACON Automation System
DA	Descent Advisor
DME	Distance Measuring Equipment
FAA	Federal Aviation Administration
FANS	Future Air Navigation System
FAST	Final Approach Spacing Tool
FAR	Federal Aviation Regulations
FMS	Flight Management System
GPS	Global Positioning System
HDR	High Density Rules
ICAO	International Civil Aviation Organization

IFF	Identification Friend or Foe
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INS	Inertial Navigation System
MEL	Minimum Equipment List
MLS	Microwave Landing System
MNPS	Minimum Navigation Performance Standards
MoA	Memorandum of Agreement
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
PSA	Precursor Systems Analysis
RA	Resolution Advisory
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
RNAV	Area Navigation
RNP	Required Navigation Performance
RVR	Runway Visual Range
SOP	Standard Operating Procedure
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
TM	Traffic Management
TLS	Target Level of Safety
TMS	Traffic Management System
TMU	Traffic Management Unit
TRACON	TerminalRAdar CONtrol
TSO	Technical Standard Orders
VFR	Visual Flight Rules

CHAPTER 1: EXECUTIVE SUMMARY

The radio-defined skyways that layer our national airspace resemble in many ways an interstate highway system.

The web of skyways that cover the national airspace resemble in many ways an interstate highway system. The invisible roadways and intersections are defined by ground-based radio beacons. Air Traffic Controllers are the traffic cops who direct airplanes from departure to destination.

The nation is divided by invisible jurisdictional boundaries into 22 air route traffic control centers. Control shifts from one en-route center to the next as aircraft navigate through the skies, often under partial and, more and more commonly, total automation.

Air Traffic *Management* (ATM) is the correct comparison for AHS.

The purpose of this Precursor Systems Analysis study is to compare the National Airspace System (NAS) to an Automated Highway System (AHS) and derive as many lessons learned and recommendations as possible. ATC began, in the form we recognize it today, during World War II, when dramatic increases in mostly war-related air traffic required active control of aircraft. This resulted in the skyways system we now have today.

Figure 1. Similarity Between Air Traffic Management and AHS

The ATC system remained relatively unchanged until 1982, when the air traffic controllers went on strike. The few remaining controllers could not handle the traffic load, and it became apparent that “old methods” of traffic management, i.e., stacking aircraft in holding patterns (like traffic jams on a freeway), would not be sufficient in the future if air traffic increased at the projected rates. So for the last decade the FAA, NASA, and industry have been developing systems, modifying procedures, and developing standards for increasing system efficiency without compromising safety. These initiatives and programs fall under the umbrella term—Air Traffic Management (ATM).

Improvement in communication, navigation, and surveillance technology and the intelligent use of automation is at the heart of ATM (and AHS).

Many of the solutions for improving system efficiency have involved technology improvements in three key technology areas: communications, navigation, and surveillance. The impact of GPS navigation alone is dramatically changing the ATM system. Many believe that the ultimate goal of the autonomous vehicle, an aircraft able to take off and land anywhere at any time, is now within reach.

In addition, many of the systems and solutions for improving safety and efficiency have also involved the introduction of automation tools—either in the pilot’s cockpit, at the air traffic controller’s console, or at sector-wide Traffic Management units.

Chapters 2, 3, and 7 offer the best summaries for the hurried reader.

This report documents the results of this comparable systems analysis—the comparison of Air Traffic Management to Automated Highway Systems. The next section, chapter 2, establishes this comparison in more detail. It shows that the two systems are similar and provide useful insight into one another no matter what perspective you have: functionally or operationally. In chapter 3, we discuss five major themes, or trends, occurring within the aviation world today that are directly pertinent to AHS. For the hurried reader, chapters 2, 3, and 7 offer the best summary.

In chapter 4, we have chosen two dozen specific topics to compare and analyze in some depth. The topics chosen were pointed to or identified by the authors as areas of particular interest to AHS researchers and developers. We tried to organize the topics into three general categories: those that are mostly institutional in nature, or more technical, or a little of both (mixed). Figure 2 below summarizes the chosen topics.

Institutional	Mixed	Technological
´ Avoiding system fragmentation	´ Mixed vehicle types and Queuing/merging philosophies	´ Mode annunciation standardization
´ A National AHS (Interjurisdictional issues)	´ Go/no-go decision making	´ Designing for diagnosis
	´ Safety-critical communications	´ Handling inclement weather
	´ Distribution of Responsibilites	´ Lane changing
	´ Variations in procedures	
	´ Minimum equipment lists	
	´ Fail-operational versus Fail-passive	
	´ Minimum operation performance standards	
	´ Post AHS capacity limitations	
	´ Evaluation toward a 4-D system	
	´ Introduction and evolution of autopilots	
	´ Vehicle-to-vehicle communications	

C940301-07

Figure 2. ATM Issues Chosen for Comparison Analysis

In chapter 5, we look into the important problem of standards development within the National Airspace System and make recommendations for AHS. Standards development was chosen specifically because of its importance during this early stage of AHS system definition.

In chapter 6, we look at some of the current programs and initiatives within the FAA focused on improving capacity and safety through technology and automation. These programs point out to us the “holes” in the current ATM system that we can interpret as potential risks for AHS. In addition, the chosen solutions can be taken as recommendations to AHS as they are often the results of years of systems analyses and sometimes failed alternative paths.

Chapter 7 summarizes in list format the lessons learned and recommendations made in the preceding chapters.

Finally, two appendices are included that compare AHS and ATM at detailed operational and functional levels. Both exercises were performed, rather than one or the other, in an attempt to be as comprehensive as possible. For each, Lessons Learned were captured and documented.

CHAPTER 2: ESTABLISHING THE COMPARISON

Like AHS, Air Traffic Management is a relatively recent term. The International Civil Aviation Organization (ICAO) describes ATM as two integrated parts: the ground part that encompasses the traditional civil aviation functions and services, and the air part which provides additional functionality through airborne sensors, computer and air-ground links. In AHS, we use a similar definition but rather than ground and air parts, we refer to the infrastructure and the vehicle.

ATM and AHS are built upon similar communication, navigation, and surveillance (CNS) technologies.

For our purposes, exact definitions are less important than understanding that the two systems, ATM and AHS, share a significant number of needs, objectives and even the same measures of effectiveness such as "passenger hours of delay". In addition to having similar top-level objectives, the two systems are built upon similar communications, navigation and surveillance (CNS) technologies. Tops-down or bottoms-up, the two systems are very similar and the cross-fertilization of experienced knowledge and ideas will be beneficial to both.

This chapter will summarize the parallels between ATM and AHS. It will lay the groundwork, by introducing terminology and organization, for the following chapters where AHS relevant lessons learned and recommendations based on the evolution of the ATM system are discussed.

ATM IS MORE THAN ATC

Increasing system efficiency through automated Traffic *Management* is a relatively new role for the FAA.

Historically the primary role of ATC has been to ensure the safe separation of aircraft. This involves the sequencing and metering of departing and arriving aircraft as well as the resolution of potential separation violations. Traffic Management (TM) was not added until the 1980s. The impetus for change was the 1982 controller strike. Since there was an insufficient number of controllers available after the strike to manage holding stacks, the FAA instituted the flow management facilities. A redesign of the airspace was necessary to allow for flow control instead of holding. This interim system of a decade ago has now become an institution.

Thus, Air Traffic Management, of which ATC is a subset, is the correct comparison for AHS. The incorporation of Flow Management and the use of technology and automation to increase system performance all fall under the umbrella of Air Traffic Management. The block diagram in figure 3 depicts our current national Air Traffic Management system. The shadowed boxes which represent the traditional ATC functions give an indication of how the control functions of ATM fits into the overall system architecture.

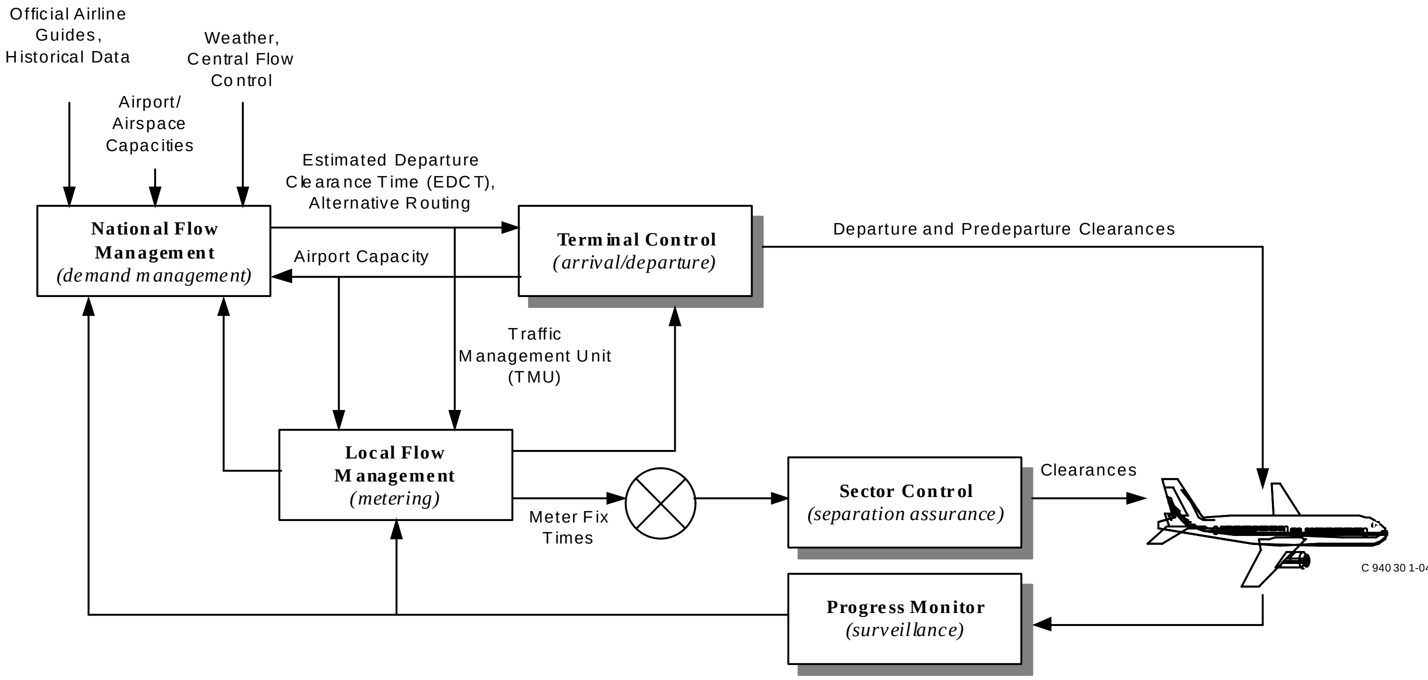


Figure 3. The National Air Traffic Management System

The addition of Local and National Flow Management Units is an important new feature of our National Airspace System and is what makes ATM an excellent comparison for AHS.

SIMILAR NEEDS, OBJECTIVES AND MEASURES

One of the most striking similarities between AHS and ATM makes itself evident in their statements of objectives. The following passage quoted from reference 1 states the International Civil Aviation Organizations (ICAO) objectives for ATM:

> *"In combination, the new CNS (communication, navigation and surveillance) systems provided under the ICAO concept will make it possible to realize a broad range of ATM benefits that will enhance safety, reduce delays, increase capacity, enhance system flexibility, and reduce operating costs."*

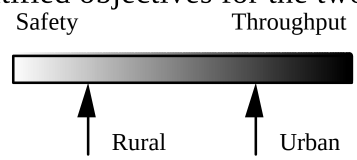
Compare this to an Advanced Vehicle Control Systems (AVCS) objective statement quoted here from the *Strategic Plan for IVHS in the United States* (3)

> *"AVCS combines sensors, computers and control systems in vehicles...for achieving much higher safety levels, ameliorating urban freeway congestion, achieving new standards of productivity, and eventually creating entirely new concepts for surface transportation services."*

Increasing capacity while maintaining (or improving) safety is the foremost objective of both AHS and ATM.

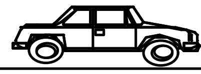
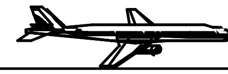
The similarity of the two statements is unremarkable when one realizes that they have arisen from the same basic need: a need for more capacity to support projected growth. Present day air traffic operations are already constrained primarily by the shortage of runway and airport facilities. In addition, planned runway and airport facilities are expected to be inadequate to meet future growth (2). Similarly, the highway systems in many urban centers in the US. have reached capacity limits and expansion to meet projected growth is prohibitively constrained by the lack of available land.

Thus, increased capacity is the driving need for both AHS and ATM; getting more vehicles through the already existing lanes and runways. However, both are constrained by the requirement that safety must not be compromised. These two primary issues, safety and capacity, are accompanied by a host of secondary objectives such as ride quality. Figure 4 summarizes some of the most commonly identified objectives for the two systems.



There is no single "best" AHS. Implementations will vary to meet regional needs.

In both systems, AHS and ATM, there is a safety versus throughput trade-off. These two objectives are not entirely independent of the other objectives but there is a very strong relationship between the two. In many ways there is a safety/throughput spectrum. The "right" or "best" AHS will not be a single line on this continuum but will vary with regional needs. For example, rural application of AHS will field implementations of AHS that weigh safety over throughput whereas heavily congested urban areas may choose an AHS that increases throughput while maintaining safety standards.

Objectives	AHS 	ATM 
Safety	Automation can improve safety. The goal of AHS is to reduce fatalities and injuries by 8%.	Current goal of FAA is maintaining safety with the increase in airspace congestion.
Throughput	Highway construction is a problem in most major cities. Delays cause stress and cost dollars. The goal of AHS is to increase volume capacity and reduce congestion.	Airport congestion reaching limits in several major cities, resulting in delays and increased costs.
Ride Quality	Reduce stress associated with travel and increase the comfort of travel.	Passenger ride comfort important in public perception of air travel safety. Minimize pilot stress.
Environment Impact	By reducing excess travel time, fuel savings will be realized as well as reduction in vehicle emissions.	Fuel costs and noise pollution considerations drive many airline design choices.
Affordability	System must ultimately be affordable in order to gain public acceptance.	Affordability is key issue in subsystem design and ñground-based vs. airborneî decisions.
All-Weather Requirements	System must function, with minimal reduction in efficiency, in all weather conditions.	Goal is to maintain capacity and safety regardless of weather conditions.
All-Vehicle Requirements	System should accommodate all vehicle types: cars, buses, trucks, etc.	ATC must accommodate all aircraft types (commuter, transport, jet, cargo), each with varying levels of instrumentation.
Gradual Evolution	Harmonize with existing system. Highways must handle both automated and nonautomated vehicles.	Until all aircraft become equipped with FMS systems, ATC must be able to handle both ñequippedî and ñunequippedî aircraft.
Promotion of Economic Activity	Make better use of existing facilities and reduce and improve effectiveness of surface transportation.	Aviation technology contributes significantly to GNP. Maintaining global leadership is beneficial to all.
Global Effectiveness	Benefit both urban and rural users of the various AHS subsystems.	System must accommodate vehicle operations in Africa as well as the U.S. Planes must be able to take off and land as safely in Kenya as in New York.
User Friendliness	Frees driverís attention requirements. Operable by all drivers (elderly, handicapped, etc.)	FMS reduces pilot workload and makes more functionality available without increased pilot effort.
Travel Reliability	Provide predictable and reliable point-to-point travel.	Improve airline scheduling needs by minimizing delays through active traffic management.
Personal Mobility	Accommodate more users and allow for wider range of driver skills.	Promote air travel through lower user costs by operating a more efficient system.
Seamless Operation	Avoid jumps in service between neighboring jurisdictions and promote full integration with other transit services.	Reduce system fragmentation problems both nationally and internationally.

C94 030 1-05

Figure 4. Similarity of AHS and ATM System Objectives

The same needs and the same objectives results in similar measures of effectiveness. Better Air Traffic Management is measured by the increase in air carrier operations in the system while keeping the same level of safety. Better AHS is measured by increased vehicles/hour/lane with increased safety. In addition, both systems are highly complex and interconnected. For instance, actions which attempt to manage traffic at one location in the system often can cause both delays and under utilization at other locations. The methods being adopted for handling this inter-connectivity in the ATM arena are directly applicable to AHS. Chapter 6 discusses some of the new initiatives within industry, NASA, and the FAA to address these complicated problems.

SIMILAR OPERATIONS

A natural and intuitive way to subdivide a large and complex system into manageable pieces is to break the system down into its "operational elements". This exercise was done for AHS by the *Human Factors Design for AHS* contractors (5). The operational functions, once defined and organized into an origin-to-destination manner, can create a Concept of Operation for the system which is a convenient tools for communicating the behavior of the system.

AHS and ATM share many operational functions; everything from vehicle check-in through to transition back to manual control and vehicle check -out.

Not surprisingly, most of the AHS operational elements map directly onto a similar operation in ATM. Figure 5 pictorially depicts origin-to-destination concepts for the two systems and identifies many of the common operations. Many of the operations may ultimately be implemented in very different ways, nonetheless, both systems must perform the operations. In addition, many of the comparable operations may share similar performance and/or reliability requirements. For example, in both systems a *Vehicle Check-In* operation is performed. In ATM, this is performed while the airplane is parked at its gate. In AHS, this may occur while the vehicle is in motion in a transition lane or on an entry ramp. For both systems however, confirmation of vehicle readiness, or health, is required and minimizing the time required for check-in is a design goal.

Appendix B of this report summarizes the AHS operational functions and gives a detailed departure-to-destination example within ATM. The matching AHS operations are called out for easy reference.

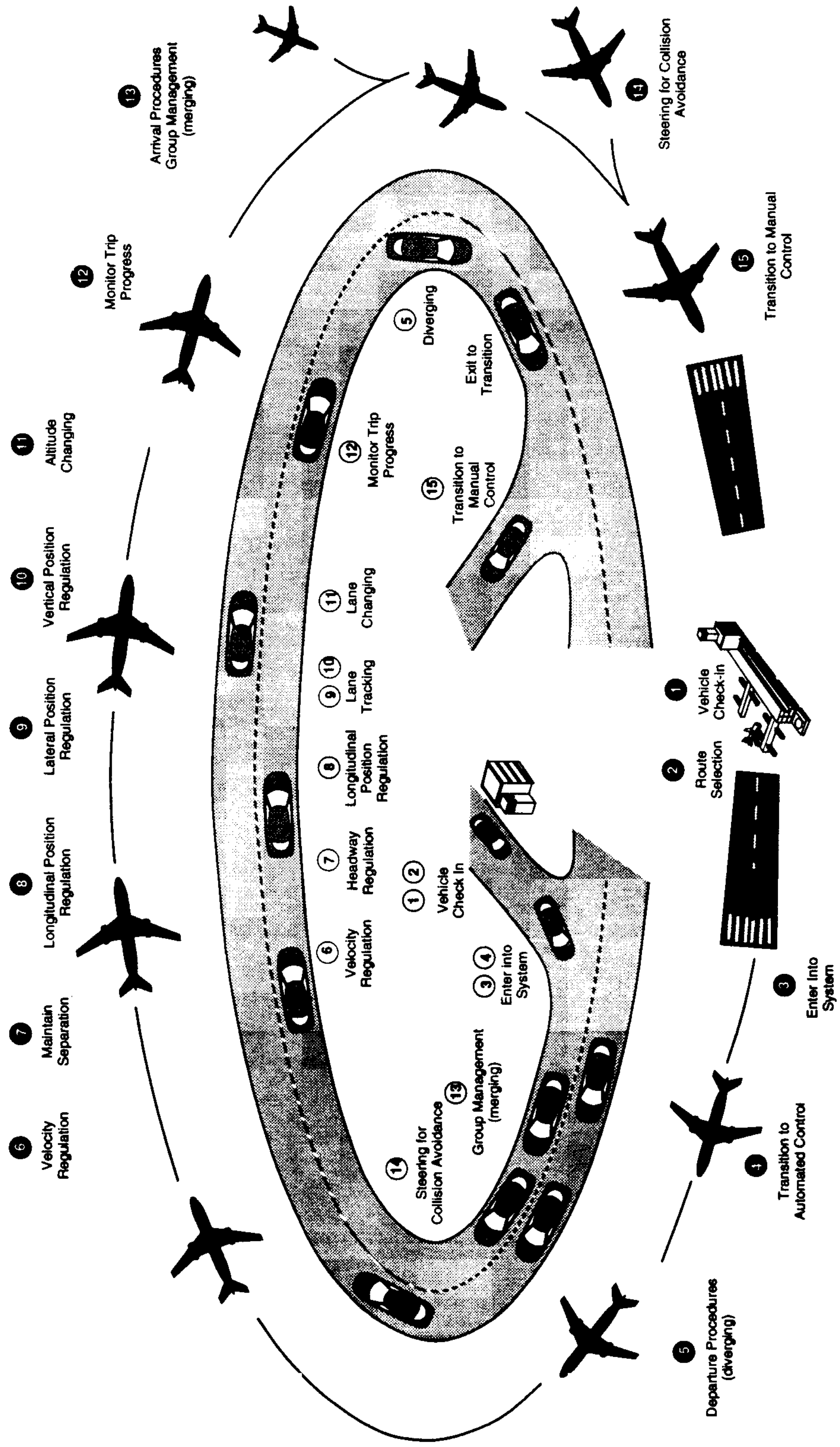


Figure 5. Similarity of Operational Elements Between ATM and AHS

SIMILAR FUNCTIONS

Many of the *Precursor System Analysis for AHS* studies have done functional decompositions of an AHS in order to identify the functional requirements of the system. This is a common systems engineering methodology which when successfully completed ensures that the system is capable of performing the desired mission scenario. Because of the large number of functions required to define a system as large and complex as an AHS, is it convenient to organize the functions into a layered or hierarchical architecture. A model architecture for AHS has been proposed by Varariya, et. al in reference 4. The architecture includes five layers and each layer accomplishes a unique traffic management or vehicle control task with minimal support from neighboring layers. **The layered architecture being proposed for AHS is consistent with the current ATM system architecture.**

This reference architecture is independent of an implementation. At each level there is a definition of what that level requires, what is does, and what it provides. The lines to and from each layer represent lines of communication. We have mapped the ATM system onto this architecture model and found a good correlation with even the lines of communication being consistent. We feel this is significant as the ATM system is an already implemented and proven system that has evolved over the last decade. The two system architectures are depicted in figure 6.

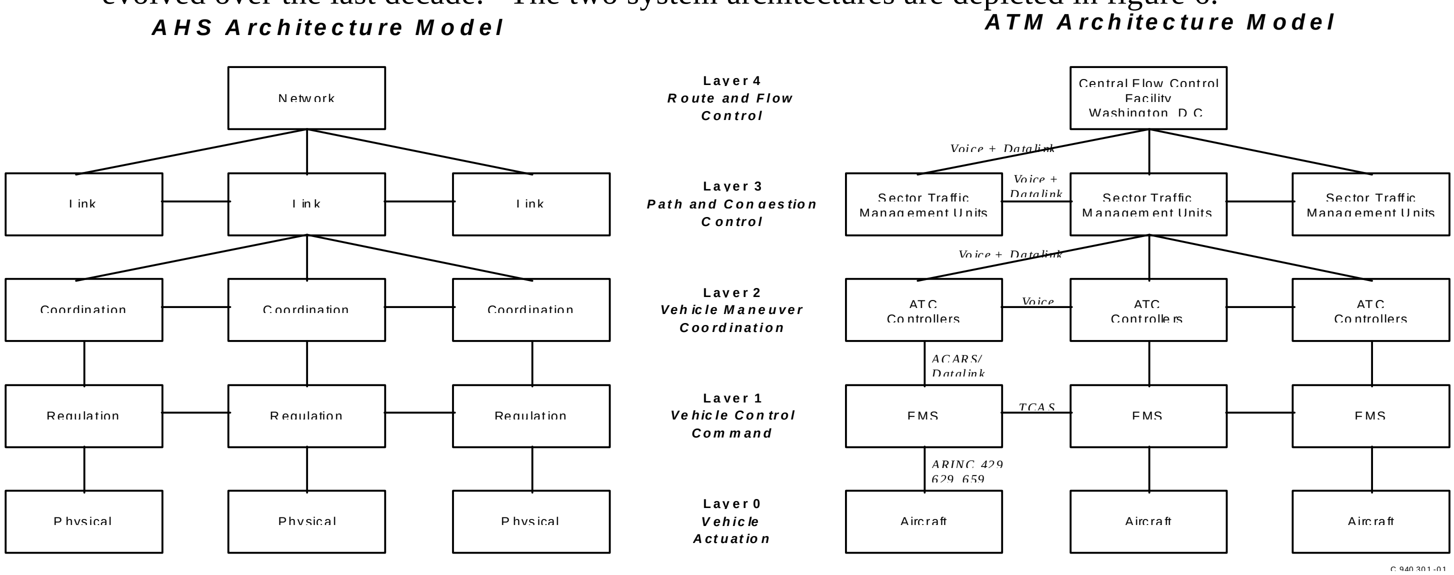


Figure 6. AHS Reference Architecture and ATM System Architecture

The ATM architecture depicted in figure 6introduces some ATM terminology that is used later in this report. For each layer of the architecture there are unique elemental functions dealing with sensing, monitoring, communication, decision making and actuation. In appendix A of this report the AHS elemental functions for each architecture layer are listed in table format. The corresponding ATM function is identified and relevant issues and lessons learned are identified for each function.

SIMILAR TECHNOLOGIES

Perhaps the most obvious similarities between AHS and ATM are the technologies involved. There are specific technologies that are required for an AHS no matter what the eventual implementation looks like. For example, vehicle guidance, navigation and control will be required in any implementation. The degree of vehicle autonomy may vary significantly from one implementation to another but there will have to be navigation sensors and control processors. **AHS and ATM are built upon the same core technologies: Communication, Navigation and Surveillance.**

In 1983 the International Civil Aviation Organization established a special committee on Future Air Navigation Systems (FANS). FANS was responsible for studying, identifying and assessing new concepts and new technologies for the coordinated evolutionary development of air navigation for the next 25 years(1). The committee organized its technology recommendations into three collective areas: Communications, Navigation and Surveillance (CNS). We have borrowed this categorization for this report;. Thus, many of the following discussions are organized around the three technologies: communications, navigation and surveillance. Figure 7 highlights the three technology areas for both AHS and ATM.

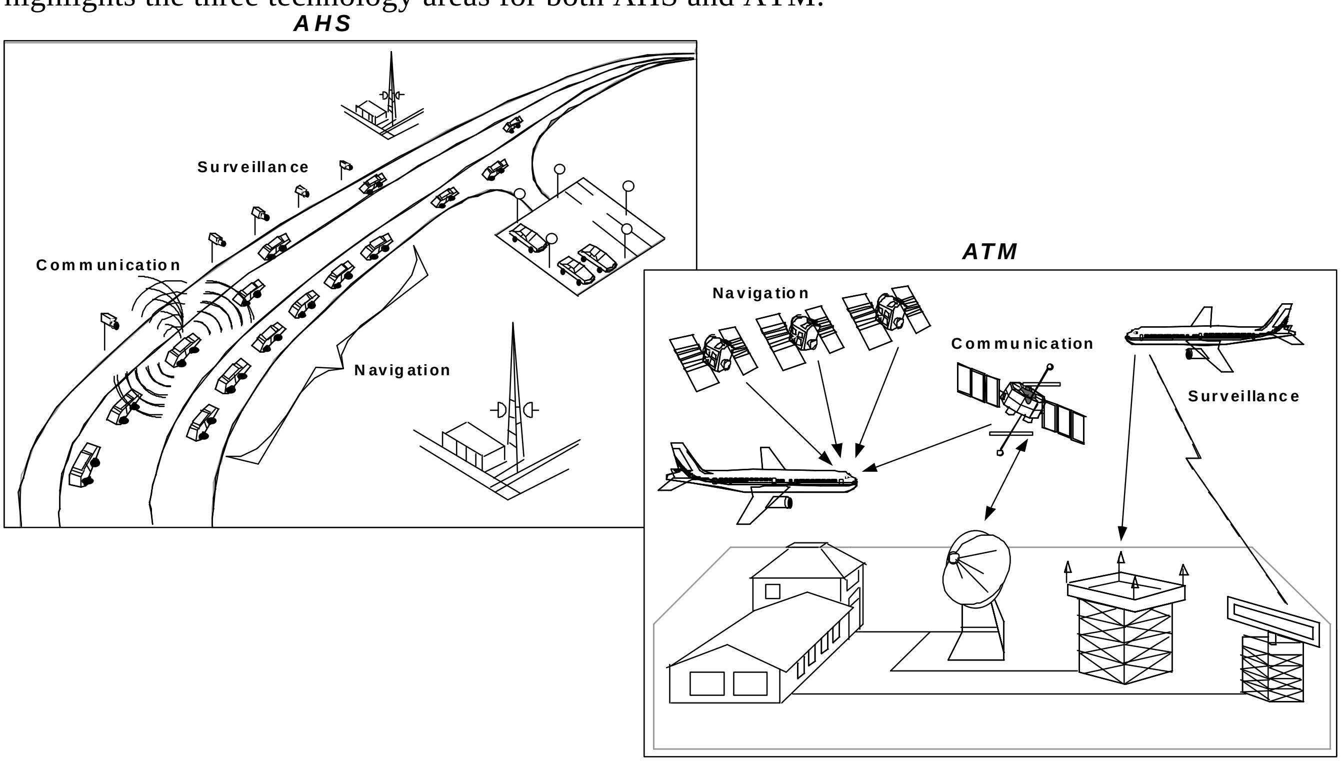


Figure 7. CNS Technologies for both AHS and ATM

The CNS technologies that form the basis of the international Air Traffic Management system are listed below in figure 8. Although some of the needs and constraints AHS differ from those of ATM, and as such, different technological soultions may evolve, the list is included here as a refernce point for AHS developers. These technologies have been successfully applied to meet the strict reliability and operational standards required for aviation use.

Communication	Navigation	Surveillance
´ VHF Voice/Data ´ Aeronautical Mobile Satellite Service Voice/Data ´ Secondary Surveillance Radar Mode S Data Link ´ Aeronautical Telecommunication Network (ATN)	´ Area Navigation/Required Navigation Performance (RNP) ´ Global Navigation Satellite System (GNSS) ´ Barometric Altimetry ´ GNSS Altitude ´ Inertial Navigation System/ Inertial Reference System (INS/IRS) ´ Microwave Landing System (MLS)	´ Automatic Dependent Surveillance (ADS) ´ Secondary Surveillance Radar Mode A/C or Mode S

Figure 8. CNS Technologies used in Aviation

The choice to categorize the necessary technologies in this manner is significant. In many ways communication, navigation, and surveillance are like three legs that hold up the stool of Air Traffic Management. The system is the most efficient and the safest when all three components are working.

The concept of threeindepent systems, compensating for each others failures and limitations, is an important one that is referred to many times in this report. It is a design philosophy strongly recommended by the authors. There will be instances in AHS, when one of the three components may be difficult to implement—for example, in ATM radar-based surveillance is impossible over most of the oceanic regions. In these instances, the other two components can be used to compensate—in thisexmple, precise vehicle navigation systems and satellite communication systems report vehicle position directly to the air traffic controller. This position reporting system is called Automatic Dependent Surveillance. It is important to note that when *independence* of the three systems is lost, the system reliability is comprimised. In this such situations, operational standards are written to reflect the loss of safety. Understanding this trade-off is key to the successful development of AHS.

SIMILAR ISSUES, RISKS AND LESSONS LEARNED

We have established that the two systems, ATM and AHS, share a remarkable number of paradigms, parameters, and problems. Thus is it not surprising that many of the assumptions, issues, solutions and lessons learned over the last decade within the ATM community are directly applicable to AHS.

Even though the core CNS technologies are the same, the AHS system is in many ways a more challenging problem.

Clearly, the two systems are not identical however. One of the most immediate differences that comes to mind is that pilots are highly trained professionals and the average driver is not. Another primary difference is the number of vehicles the two systems must accommodate. A busy international airport will handle on the order of 100 aircraft, arrivals and departures, per hour during peak periods, whereas a single highway lane can see as many as 2600 vehicles per hour during rush hour. In addition, ATC maintains vehicle separations on the order of 1/2 miles in congested terminal areas and up to 60 miles in trans-oceanic corridors. For AHS, vehicle separation on the order of 1 to 30 meters are being considered. As a result, communications, control, and surveillance functions will all require higher bandwidth and tighter resolution than is currently required in ATM. Even though these differences are significant, there are many more areas than not in which these two systems are similar and where lessons learned are directly applicable.

Similar objectives, similar operations, similar functional requirements and similar technologies results in similar issues, risks and lessons learned.

The remainder of this report discusses some of the lessons learned in selected areas within ATM that the authors have found, through conferences and personal interactions, to be of current interest to AHS developers. Under the Human Factor Design for AHS contract a comparable systems analysis was performed that looked specifically at the interaction of the pilot with the flight deck automation. Thus, care was taken not to duplicate efforts and the reader is encouraged to refer to the final report of that study(6) for details on the pilots roles, responsibilities and reactions to flight automation as a model for AHS.

CHAPTER 3: TRENDS IN AVIATION RELEVANT TO AHS

Trends often indicate changes in fundamental philosophies. Understanding the reasons for these changes are the Lessons Learned that we are seeking.

There are a number of trends occurring in the aviation industry today that highlight some underlying changes in philosophy. These changes are occurring for a multitude of reasons, but common to all is that the old “methods” were limiting growth—either in terms of adding new capability or in terms of improving efficiency and capacity. The general trends identified below are all directly applicable to AHS. Many of the topics below are discussed in more detail in other chapters of this report and are summarized here for the reader’s convenience.

Figure 9 lists the five major themes summarized in this chapter.

From Centralized to Distributed Control
From Traffic Control to Traffic Management
From Technology Derived to Technology Independent Standards
From Manual to Automated Control: The Role of the User in AHS
From Today's System to a Safety Critical System

Figure 9. Five Major Themes Summarized in This Chapter

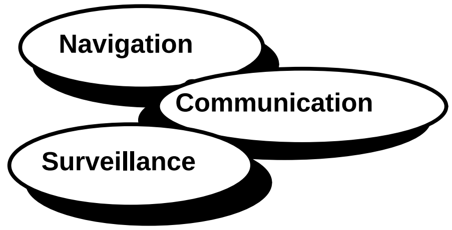
FROM CENTRALIZED TO DISTRIBUTED CONTROL

ATC is a centralized system—all communication goes through ATC. As capacity demands grow, this centralization has become a bottleneck.

A subtle but significant change in the aviation world today is the move away from a centralized air traffic control to a more distributed system. Air traffic control has been a centralized system. All communication goes through ATC. An aircraft *talks* to ATC, and ATC passes any pertinent information on to neighboring aircraft. This form of centralized control has become a significant bottleneck in today’s crowded skies. Technologies such as digital datalink between the aircraft and ATC are making this information exchange faster, but nonetheless, the ability of ATC to relay information from aircraft to aircraft will always be a limiting factor in system capacity.

The vehicle-based TCAS system has introduced an element of decentralization.

A change occurred in the early 1990s when the FAA mandated the use of TCAS (Traffic Alert and Collision Avoidance Systems) on all commercial aircraft of 30 seats or more. TCAS introduced the first vehicle-to-vehicle communication within ATC. TCAS-equipped aircraft continually broadcast their current position (and sometimes intent) and then listen for other aircraft in their vicinity. TCAS alerts the pilot of nearby traffic and will advise the pilot to change altitude if it anticipates a loss of safe separation with approaching aircraft.



This vehicle-to-vehicle transponding and receiving is *transferring* some of the ATC's surveillance authority to the individual vehicles operating within the system—a small but significant change from an entirely centralized system to a distributed system.

Although there were significant growing pains with the introduction of TCAS, the benefits are more than evident. In addition, the system, which was intended to "improve safety," is already *unofficially* being used by pilots for altogether different (and creative) purposes—another indication that the move away from centralized control is a welcome change to the users of the system.

The Autonomous Vehicle

The trend in aviation is toward smart vehicles. AHS should follow suit.

A trend related to this concept of centralized versus distributed control is the trend toward the autonomous aircraft. For a long time, airlines have dreamed of the autonomous aircraft: an aircraft capable of taking off and landing at any airport, at any time, regardless of the weather. This grew out of a frustration with the limitations imposed by ATC—limitations that were often perceived to be the result of poor administration by the FAA rather than technological limitations. The technology on most commercial transports today is significantly more advanced than the ground-based equipment owned and operated by FAA. Aircraft equipped with a Flight Management System, one-third of the total operating commercial transport fleet today, are capable of full three-dimensional auto-flight from takeoff (at 400 feet of altitude) to final approach. If the aircraft is equipped with autoland capability, the vehicle could conceivably fly from near takeoff through landing and rollout without the pilot ever touching the controls.

The FAA has been unable to keep pace with equipment manufacturers. Highly capable aircraft are significantly limited by aging ground-based equipment.

Although the aircraft is fully capable of precisely navigating a three-dimensional optimal path from takeoff to landing, aircraft are commonly restricted by ATC to fly along highly restrictive airways, which often add hundreds of miles of travel per trip. In addition, for an aircraft to perform an autoland, the airport must be equipped with appropriate instrument landing system, and only the busiest airports can afford the expensive equipment. In essence, ATC has not kept pace with the available technology, and the highly automated vehicles are not able to take advantage of their technological capability.

Thus the airlines have always hoped for a certifiable aircraft that was capable of full autoflight without the aid of any ground-based equipment. Many think that the Global Positioning System (GPS) may be the breakthrough the airlines have been waiting for. If the integrity and reliability of GPS proves sufficient for autoland, and ATC modifies its operational procedures to handle direct routing for aircraft equipped with RNAV and Automated Dependent Surveillance (a position reporting system), the airlines will have their autonomous aircraft.

Cost/benefit analyses must take into account the extreme inter-connectivity of such a complex system.

This trend is significant for AHS. For years, the capability of the National Airspace System has been held up by the lagging ATC system. Airline operations have been hindered by a dependence on ground-based equipment that the FAA failed to keep up to date. Although initial economic assessments may have indicated that putting one system on the ground rather than one system in every vehicle was more cost-effective, in the long run it may not have been.

Privatization of AHS may be the most efficient implementation.

To alleviate this problem, the FAA and many international aviation authorities are looking at partially privatizing ATC. This is an option the FHWA should consider for AHS if there turns out to be significant dependence of the vehicle on the infrastructure. In any case, the authors suggest developing AHS with "smart" vehicles as the long-range objective and roadside equipment filling the role of surveillance (not navigation).

FROM TRAFFIC CONTROL TO TRAFFIC MANAGEMENT

Increasing traffic demands necessitated the move from tactical traffic control to strategic traffic management.

Another trend in aviation is from air traffic control to air traffic management. For decades, the role of ATC was to *ensure the safe separation of aircraft*. This meant resolving localized conflicts when they occurred. This usually involved placing an aircraft in a holding pattern or diverting (vectoring) of aircraft. As air traffic increased, however, more and more vehicles were experiencing more and more delays due to the reactive, tactical nature of ATC. It wasn't long until controllers figured out that strategic planning could often reduce the need for last-minute diversionary tactics. Most of the new FAA initiatives in the last decade are addressing the concept of traffic management rather than traffic control.

***Inner Loop* = vehicle lane tracking, headway keeping and velocity control.**
***Outer Loop* = entry, exit, lane and route specification.**

This is a major philosophical change, and various aspects are discussed in many places in this report. Traffic management, as opposed to traffic control, is a higher order function (often referred to by control engineers as outer loop control). AHS developers should design the system with full traffic management as the long-range objective. In this way, they will avoid designing *inner-loop* controllers that are incompatible with *outer-loop* traffic managers.

Much of the AHS research to date within the United States has been focused on inner-loop vehicle control, while the Australians and the Europeans appear to be focusing more heavily on outer-loop traffic management solutions.(10) The authors recommend a more balanced emphasis since the final AHS system, like ATM, will have significant elements of both.

FROM TECHNOLOGY-DERIVED STANDARDS TO TECHNOLOGY-INDEPENDENT STANDARDS

Chapter 5 discusses in detail the development of standards within the aviation industry. It is interesting to understand how standards were developed, but it is very important to keep in mind that the whole process is currently undergoing a significant revolution. Once again, partial credit can be given to the introduction of GPS.

Subsystem performance requirements that are dependent on a specific technology will artificially inhibit the introduction of new technology and will *hinder the evolution* of the system.

Historically, equipment standards were "backwards engineered" from the capability of the current technology. New subsystems were introduced into the system if they improved safety or performance. After the subsystem proved itself in the field, the standards were rewritten to reflect the new technology. This often meant that there was only one system, the most current technology, that met the standards.

Few complained about or were even aware of the shortcomings of the process until the introduction of GPS. Suddenly there existed a new *affordable* navigation system that was fully capable of the kind of precise positioning required for autoland capability, for example, but it didn't meet the standards as they had been defined for the currently used Instrument Landing System (ILS). The standards had been written to describe the performance of an ILS, and GPS did not *behave* in the same manner. The standards that had been written were technology-dependent (defined by ILS), and this was delaying the introduction of GPS.

Figure 10 pictorially demonstrates this concept. The three labeled "boxes" represent the error balls, or performance accuracy, of the three navigation systems used by autoland systems: Instrument Landing System (ILS), Microwave Landing System (MLS), and GPS. On the runway, touchdown dispersion areas are drawn. The FAA standards for autoland systems were written such that the autoland navigation system performance has an error box similar to the ILS box. The figure shows that the GPS system does not meet the ILS-derived standards in the vertical dimension. GPS, however, has a smaller touchdown dispersion than ILS.

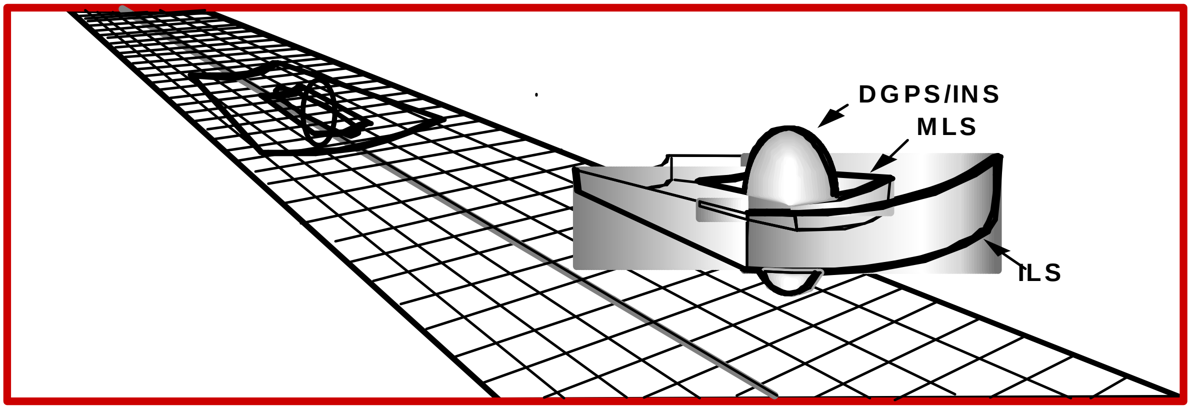


Figure 10. Example of the Limitations of Technology-Derived Standards

As a result of such obvious limitations, the FAA is taking another look at its standards development processes and is now deriving *technology-independent standards*. This means looking at the system and defining what is required by the system for safe and efficient operation, not at what the technology is capable of. The new methodology addressing the above problem is called the Required Navigation Performance (RNP) tunnel concept. Many of the techniques being redefined for this new concept are directly applicable to AHS, and the authors strongly suggest using these methodologies and techniques for AHS.

AHS should avoid technology-derived standards by doing thorough system analysis and determining the actual *system* requirements.

It is recommended that the FHWA be very conscious of avoiding similar problems. Standards should be derived based on what is needed by the *system* to function safely and not backwards engineered from the available *technology*. In other words, care must be taken to define the standards based on what we *need*, not on what we are *capable* of today.

FROM MANUAL TO AUTOMATED CONTROL: THE ROLE OF THE OPERATOR IN AHS

The issue of *who* (or what) has ultimate responsibility for the safe operation of the vehicle must be addressed before further development.

In ATM, the pilot has ultimate responsibility. This has significant implications for liability litigation.

Perhaps the key issue that must be addressed *before* design of the AHS can proceed is who has ultimate responsibility for safe operation of vehicles in the AHS. In aviation, the FAA holds pilots ultimately responsible for the safety of flight operations. This is reasonable because the Airman’s Information Manual provides the pilot with the authority to deviate from ATC instruction, Federal Aviation Regulations, and operating conventions to ensure safe flight operations. The issue of responsibility for safe operations can be placed with the user if a human is in the control loop. In a system where there is autonomous vehicle control, the issue of responsibility (and liability) becomes one that the system must bear.

Even though a firm concept of operation for AHS has not been established yet, it appears that the AHS will involve the driver relegating vehicle control and headway, keeping to some form of automated operations.

Shown in Figure 11 is a continuum of operation, from manual control to autonomous operations, developed by Billings in his treatise on “Human-Centered Automation”[9]

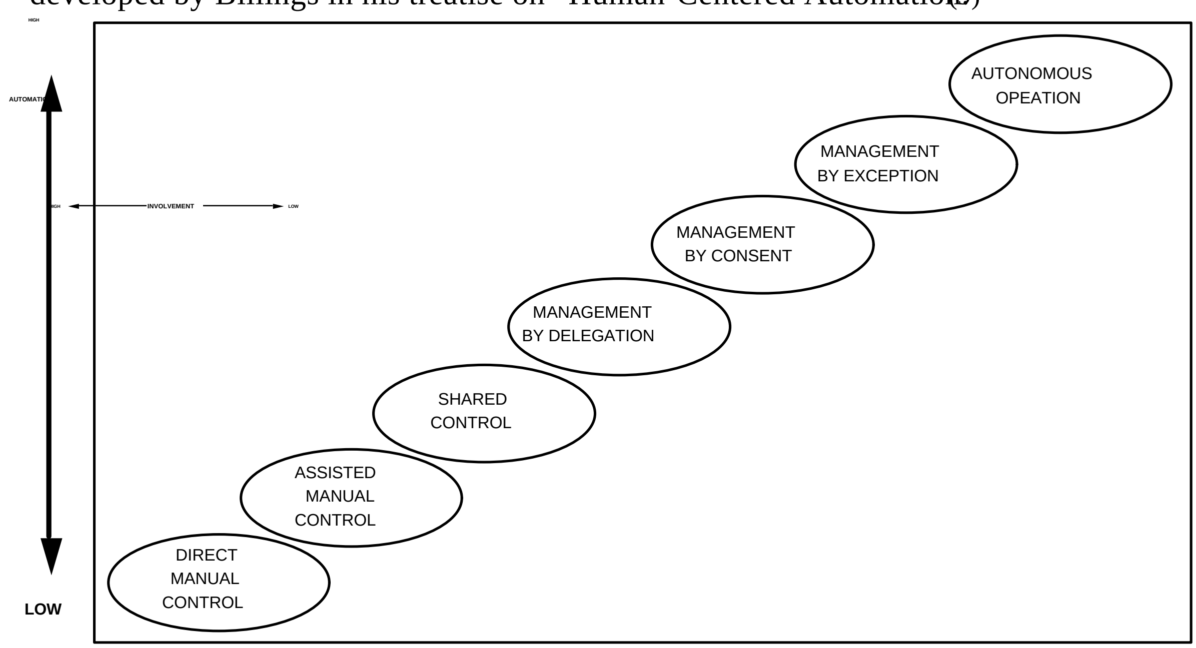


Figure 11. Levels of Automation

The AHS will attempt to connect both ends of this operation’s spectrum into one “seamless” system. A vehicle (either car or truck) will be capable of either direct manual control, as is done today, with autonomous operation to derive the benefit of increased system capacity. From our experience with flight automation, we have learned that humans are not good at the *transition* from a supervisory role to manual control. In-vehicle automation systems should minimize the requirements for manual transition through the use of fail-safe modes.

Every effort should be made to assist the driver in detecting all errors, ***including his own*****.**

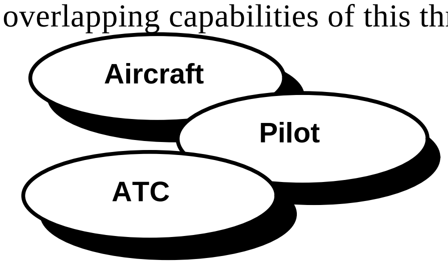
Aviation statistics for the worldwide commercial jet fleet from 1980–1989 indicate that over 70% of all accidents occur in the terminal area (takeoff and landing)—the period of heaviest workload for pilots. This is functionally analogous to entry onto and exit from the AHS. In aviation, we have learned that any schemes that add to operator workload during these critical phases of operation are suspect—particularly if they in any way decrease the operator's capacity to *supervise*. In addition, we have learned that every effort should be made to assist the driver in detecting all errors, *including his own*.

FROM TODAY'S SYSTEM TO A SAFETY-CRITICAL SYSTEM

To gain user acceptance, AHS will have similar safety requirements to today's aviation system. Thus, AHS will need an approach akin to the aviation system to meet such high reliability requirements. Today's aviation system has evolved from a pilot-only system to a system consisting of three components:

- *aircraft* as trajectory follower
- *pilot* as guardian and supervisor of the aircraft, and
- *air traffic controller* as coordinator and supervisor of the system.

Safety is ensured through the overlapping capabilities of this three-part system:



- accuracy of the *aircraft* to navigate
- capability of the *pilot* to supervise and intervene
- ability of *ATC* to monitor and take corrective action

There are two ways to achieve extremely high reliability in a system: (1) make sure every component in the system is ultra-reliable, or (2) use multiple realiable components that continuously cross check each other.

AHS should be built upon multiple levels of ***independent*** **supervision: conceptually, theoretically, and functionally independent.**

Ultra-reliability can only be assured with reasonable certainty by means of overlapping layers of supervisory failure-compensating systems.

Similar to the way ATM operates, we recommend that AHS be built upon multiple levels of *independent* supervision. The supervisory systems must be both conceptually and theoretically independent at the most abstract levels, as well as being functionally independent. The importance of this concept of independent failure-compensating systems cannot be emphasized enough. System reliability is achieved through compensating, independent systems, not through gold-plated electronics. Overspecifying the reliability requirements of AHS subsystems may drive the cost of an AHS high enough to prohibit its implementation and may not be necessary to achieve the desired target level of safety.

AHS should adopt the FAA safety criticality classification process but should re-derive the reliability numbers that define those classifications.

For deriving reliability requirements, consider using the Risk Tree Methodology currently being developed by the FAA.

The FAA Advisory Circular 25.1309-1 classifies aviation systems into three levels of criticality: critical, essential, and nonessential. The authors recommend that AHS designers adopt this safety criticality classification concept—but that we reevaluate the probability of failure specifications (numbers such as 1∞ 10^{-9} probability of failure per hour for critical systems). New techniques, such as Risk Tree Analysis, are being developed within the aviation community to do specifically this. These new methods are directly applicable to and recommended by the authors for AHS.

Criticality Classification	*Effect of Loss of Function*
Non-Essential	No significant reduction in vehicle or operator ability.
Essential	Some reduction in vehicle capability and operator ability to cope with adverse situations.
Critical	Prevent safe operation.

Figure 12. Recommended AHS Criticality Classifications

Safety-Critical Hardware

Once a subsystem has been classified as safety-critical, analysis is performed to allocate an acceptable level of *risk* to that subsystem. This risk allocation is expressed as a reliability requirement on the hardware.

It is interesting and useful to very briefly review the risk allocation process that forms the philosophical basis of the FAA requirements for safety-critical hardware systems. The following is summarized from reference 7:

A Target Level of Safety has to established for AHS before significant system design can proceed.

> The overall safety of the U.S. National Airspace System, based on approximately 30 years of flying history data, is a probability of hull loss of 10^{-6} per flight hour. This is referred to as the Target Level of Safety (TLS) for the entire National Airspace System. Historically, about 10% of the total accidents, or 1 ∞ 10^{-7}, have been attributed to vehicle system problems (power, control, electronics,
> . . .). It is awkward however to place a reliability requirement on the vehicle because it is not possible to say that a requirement has been met until all systems are collectively analyzed. For this reason, it was assumed arbitrarily that there are 100 potential failure conditions in an airplane that could contribute significantly to the cause of a serious accident. The allowable risk of 10^{-7} was thus partitioned equally among these 100 conditions, resulting in a risk allocation of 10^{-9} to each. The agencies therefor concluded that the acceptable upper risk limit for an identified catastrophic system related failure condition would be 10^{-9} for each hour of flight.

Attempts to achieve substantial system-level reliability by requiring ultra-reliable subsystems (gold-plated electronics) are misguided, impractical, and *costly.*

This summarizes the FAA's historical notion of risk allocation. They require that safety-critical vehicle subsystems be designed such that failure conditions that lead to catastrophic accidents are constrained to occur once in a billion hours. It is important to understand however that compliance with a 10^{-9} risk per hour specification cannot be measured. We *conjecture* that it can be determined through analysis using such methods as Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA); however, statistically, we cannot prove compliance. Figure 13 summarizes the certification process (adopted from the FAA's certification process).

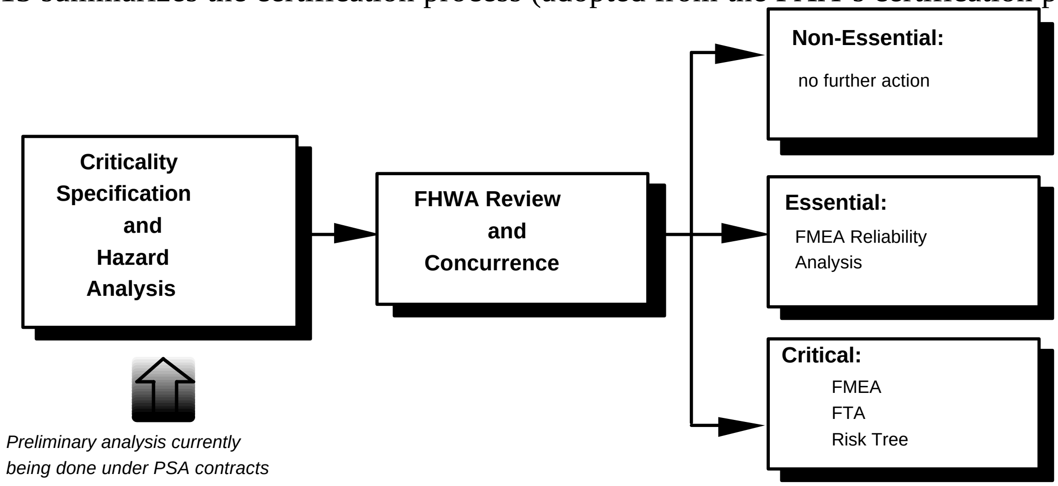


Figure 13. Summary of Hardware Certification Process

Certification of safety-critical systems contributes significantly to their cost. For AHS to be cost-effective, we must reevaluate the certification process used today by the FAA—a first step being the reevaluation of the reliability requirements for safety-critical and essential hardware.

Safety-Critical Software

Ultra-reliability of safety-critical software cannot be *verified*.

As more and more safety-critical functionality is achieved with software rather than hardware, it is pertinent to comment on a few software-specific issues and lessons learned from our decade or so of experience in aviation.

Similar to the problem with verifying the reliability of hardware, formal verification of complex software cannot be achieved. Unless the software is very simple, exhaustive testing cannot be accomplished. For example, to verify a failure rate of $< 1\ 10^{-8}$ would require 10,000 machines running in parallel for 114 years. Over the past decade, we have developed a number of methodologies and techniques to improve software reliability. These strategies are based on the concept of introducing redundancy (N-version) or avoiding, isolating, or tolerating faults. Although these methods may increase reliability, none of them can be used to *verify* the reliability of the software.

Many software errors can be traced back to the *specification* . . . as undocumented *requirements*.

One interesting lesson we have learned from our experience in writing safety-critical software for various aircraft systems is that many software errors have been traced back to the software *specification*. They were design pathologies (such as divide by zeros) or simply overlooked requirements.

In addition, a significant number of software errors are discovered at system integration and testing, and these usually involve timing problems related to the exact timing of the storage and retrieval of data. Redundant software written in different languages (N-version method) addresses this problem by adding a degree of independence, but it does not eliminate it.

Overall system reliability must be achieved through *independence*, not through unverifiable subsystem reliability requirements

Software developers of safety-critical and essential software should focus on the most cost-effective method for achieving increased reliability using a mix of all methods. It is important to recognize that it is not humanly possible to find all the design errors in a complex software system. Truly exhaustive testing is not feasible, and no formal methods exist to formally verify ultra-reliability. Once again, we emphasize that overall system reliability must be achieved through *independence*, not through unverifiable subsystem reliability requirements.

One More Comment on the Topic of Reliability—

The final topic of this chapter ties together the last two themes: system reliability and the role of the operator.

In control theory, there is a concept referred to as the "conservation of dirt." We have adopted this concept from the control theorists and applied it here to system *reliability*. There is no formal proof for this "law," but our years of experience in designing safety-critical systems for cockpits confirms our intuition. In this law is a powerful message for AHS.

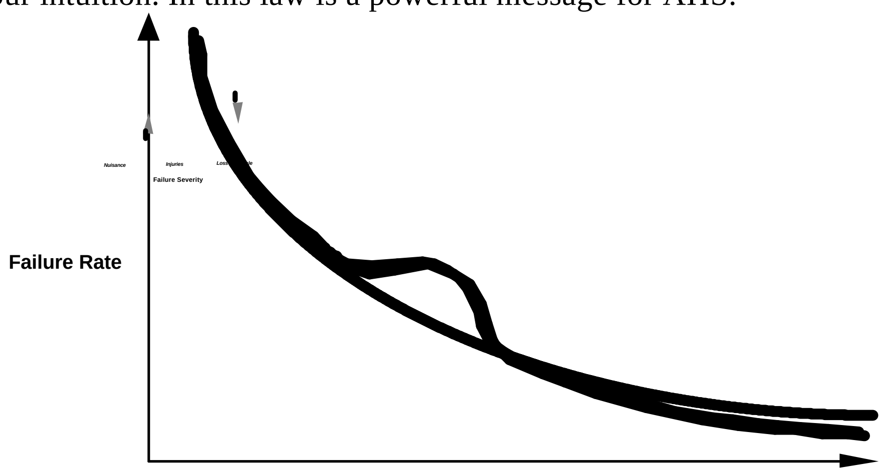


Figure 14. Failure Rate versus Severity Sensitivity Curve

The "conservation of dirt" principle applied to reliability is defined as follows. Considering Figure 14, our "law" states that there is some minimum area under the shown sensitivity curve that is fixed. If this conjecture is true, this implies a failure rate versus severity tradeoff.

Thus, if we try to decrease the "tails" of that curve we will by necessity create an increase somewhere else under the curve to keep the area constant. In other words, if we try to dig a hole in one location, we inadvertently create a hill in another location—hence the "conservation of dirt" principle. This concept is shown in Figure 15.

Failure Rate

Failure Severity

Figure 15. The “Conservation of Dirt”

There comes a point where decreasing the error tails of equipment may actually DECREASE system safety.

The significance of this is to understand the if we try too hard to push the error tails down, we will eventually see an increase in nuisance-type errors. These nuisance errors, often false alarms, will ultimately significantly tax the driver’s capacity to supervise. Thus, we may actually be *decreasing* the overall system safety by trying too hard to reduce the tails of the failure sensitivity curve. This is a very powerful concept and another argument *against* specifying unverifiable reliability requirements for safety-critical subsystems on AHS. This expensive approach is misguided and may ultimately cost us an AHS.

CHAPTER 4. SELECTED ISSUES, RISKS AND THE LESSONS LEARNED

In this chapter, we have chosen two dozen specific topics to compare and analyze in some depth. Each of the topics below represents an *issue* or *risk* for AHS. The topics chosen were pointed to or identified by the authors as issues of particular interest to AHS researchers and developers. We tried to organize the topics into three general categories: those that are mostly institutional in nature, or more technical, or both institutional and technical (mixed). Figure 16 summarizes the chosen topics.

Institutional issues are those that involve system requirements and policy from the organization that administrates the system. In the case of ATC/ATM, the Federal Aviation Administration (FAA) has the ultimate responsibility for the system, including specification and requirements definition as well as staffing of the personnel to support operations. The FAA's control of the ATC infrastructure is analogous to roadside control for an AHS. Technology issues are those that involve specific equipment utilization to make the system functional under all anticipated conditions.

Institutional	Mixed	Technological
´ Avoiding system fragmentation ´ Interjurisdictional issues (A national AHS)	´ Queuing/merging philosophies ´ Go/no-go decision making ´ Safety-critical communications ´ Centralized vs. distributed control ´ Variations in procedures ´ Minimum equipment lists ´ Fail-safe/fail-op/fail-passive ´ Minimum operation performance standards ´ Required navigation performance ´ Post AHS capacity limitations ´ Evaluation toward a 4-D system ´ Introduction and evolution of autopilots ´ Vehicle-to-vehicle communications ´ Handling of mixed vehicle types	´ Mode annunciation standardization ´ Designing for diagnosis ´ Handling inclement weather ´ Lane changing

C940301-07

Figure 16. Selected Topics for Comparison of ATM to AHS

The discussion for each topic begins with a paragraph on why this selected issue is relevant to AHS. This is followed by a several-paragraph discussion on how that particular issue is handled within the Air Traffic Management world. Each issue discussion is concluded with a succinct Lesson Learned that is highlighted in a sidebar.

SELECTED INSTITUTIONAL AND TECHNOLOGICAL ISSUES

It is not too surprising that most of the *issues* and *risks* that are of primary interest to AHS developers this early in the system definition are not purely technical in nature but a combination of technical and institutional or societal concerns. Thus, most of the selected topics fall under this first category. As is apparent from the list above, the aviation world has parallels in numerous areas of comparison to AHS. The following topics are in no particular organization and can be read in any order.

Mixed Vehicle Types and Queuing/Merging Philosophies

Implications for AHS—The AHS concept will address the mechanization of how vehicles will transition to automated control. The mixture of vehicles on manual and automated control becomes crucial in transition areas (lanes).

***Lesson Learned*—The AHS will be faced with vehicles of varying performance. Quotas for permitted usage by varying vehicle types may need to be established.**

Related Issues from Air Traffic Control/Air Traffic Management—The analogy with ATM is the mixture of advanced aircraft and general aviation aircraft around the airport areas. The biggest difference here is the speed at which the two classes of aircraft operate. When merging these two types of aircraft, the slower one places an accommodation requirement to increase interaircraft spacing; the slower aircraft must be given a "head start" on larger aircraft because of the natural closure rate of the faster moving jet. Unfortunately this spacing accommodation is in conflict with the spacing requirement based upon gross vehicle weight. The larger the aircraft, the larger the in-trail spacing requirement due to longer wake vortex dissipation rates for larger aircraft. The controller is then faced with the following dilemma: to accommodate a slow-moving aircraft in a stream of larger, faster jets, the controller must make a large space between the slow mover and the jet ahead of it and keep the next jet far enough back that it won't overtake a jet producing dangerous wake vortices.

Mixed-vehicle-type traffic limits capacity.

Currently, the FAA has a policy in place to address the mixed-aircraft merge at airports. The policy consists of limiting the number of dissimilar users. For example:

Chicago O'Hare International Airport
120 airline jet operation/hour
25 regional airline (turbo-prop)/hour
10 general aviation (slower prop)/hour

La Guardia International Airport
48 airline jet operation/hour
14 regional airline (turbo-prop)/hour
6 general aviation (slower prop)/hour

Washington National Airport
37 airline jet operation/hour
11 regional airline (turbo-prop)/hour
12 general aviation (slower prop)/hour

According to *Aviation Week & Space Technology* (4/18/94, p. 38), the FAA is currently considering changing the High Density Airport Rules (HDR); the following are being considered as options:

- Managing traffic by flow control techniques.
- Lifting High Density Airport Rules completely.
- Increasing the number of slots per hour available at each airport.
- Changing the time frame allotted to slots.
- Continuing to use the HDR in its current form.

AHS administrators must understand the balance between *equitability* and *capacity*.

In the upper Midwest regions, Center Controllers are trying a new approach of segregating fast and slow traffic along parallel en-route airways. This is a significant change from the old "first come-first serve" philosophy. This old philosophy, although equitable, limited the capacity of the system to least capable user.

Managing the traffic by flow, instead of a blanket policy by aircraft type, requires the application of Air Traffic Management technologies. These technologies allow the controller to predict time of arrival minutes into the future based upon current vehicle state. In the future, compliance with air traffic directives may include being issued specific Required Time of Arrival (RTA) for a specific point in space (e.g., a metering fix or the Final Approach Fix) to expedite arriving and departing traffic.

Go/No-Go Decision Making

Implications for AHS—The AHS user will be faced with a number of Go/No-Go decisions in the course of operation. Included in the list will be whether to join the automated traffic flow given the ambient conditions (poor weather or visibility) and current condition of the vehicle.

***Lessons Learned*—In the implementation of an AHS, at some point the issue of a failure to merge into the automated traffic stream must be addressed. The key issue is how the driver will identify the lack of a successful merge, and the corresponding driving response.**

Related Issues from Air Traffic Control/Air Traffic Management—In aviation, both operators and equipment are rated in terms of their ability to cope with prevailing weather conditions. The first activity a pilot (or flight crew) will undertake in preparation for a flight is to determine the weather conditions to be encountered along the route and at the destination. Certain weather conditions are so hazardous as to be a threat to safety. There is obvious danger in flight near hurricanes and cyclone activity, but thunderstorms, hail, icing conditions, and even volcanic ash pose serious threats to safety as well. Additionally, the visibility along the route and, in particular, at the destination in particular affect an aircraft's ability to depart.

In AHS, the Go/No-Go decision point for safely merging into automated traffic may be dependent on vehicle type. After that "point," a vehicle is committed to executing a merger.

The act of the "takeoff" causes the Go/No-Go decision to become time-critical in a manner that is quite unique in aviation. As a heavily laden transport aircraft begins the takeoff roll down the runway, there is a point on the runway, called the "balanced field length," where there is enough pavement remaining to successfully stop the aircraft without overrunning the far end of the runway. Since the balanced field length varies with aircraft weight, ambient temperature, and runway slope, the Go/No-Go decision changes with each takeoff.

***AHS parallel*—Go/No-Go decision criteria may vary from one location to another within AHS.**

An additional complicating factor is that the flight crew has no way of demarcating the actual point on the runway, so they must use speed as an indicator instead. As the flight crew prepares for takeoff, they compute three critical speeds to be monitored during the takeoff; they are V_1, V_r, and V_2. "Vee-one" (V_1) is the Go/No-Go decision-making point. Before V_1 the flight crew is relatively confident that the aircraft can stop on the runway if maximum braking is applied; after this point, the flight crew is committed to executing a takeoff. In fact, to achieve FAA airworthiness certification, the airframe must have demonstrated the ability to take off with one engine inoperative (simulating a failure during the takeoff roll). V_r and V_2 are the rotation (takeoff) and climbout speeds, respectively.

Safety-Critical Communications

Implications for AHS—Some preliminary AHS designs have shown vehicle-to-vehicle and vehicle-to-roadside communications schemes that are "safety-critical"—in the sense that if the communication link failed, severe damage could result. To ensure safe operations, these links between the roadside and vehicles traveling in the AHS must either be fail-safe or the system must be engineered so that it is tolerant of failures such that degraded modes of operations present no hazard to the vehicles using the AHS.

***Lessons Learned*—In aviation, there are no examples of vehicle-to-vehicle or vehicle-to-ground communications that are considered *safety-critical*.**

Related Issues from Air Traffic Control/Air Traffic Management—Currently, air traffic controllers use very high frequency (VHF) radio to issue verbal commands to aircraft when they are overland. VHF radio has a line-of-sight requirement; that is, there must be no obstructions between the sending and receiving antennas. Over uninhabited areas (polar regions or oceans) high-frequency (HF) radio is used for communications.

In aviation, this communication system is considered *essential* but not safety-critical—if the communication system fails, there is degraded operation of the ATM system but no risk of severe vehicle damage or loss. The authors could think of no example systems where RF communication is considered safety *critical*.

There are specific procedures that a pilot must follow if communications are lost (usually this is a malfunction in the aircraft radio system because the ground systems have redundant radios and independent power sources in case of malfunction).

According to FAR 91.127, IFR Operations; two-way radio communication failure.

(a) General. Unless otherwise authorized by ATC, each pilot who has two-way radio communications failure when operating under IFR shall comply with the rules of this section.

(b) VFR conditions. If the failure occurs in VFR conditions, or if VFR conditions are encountered after the failure, each pilot shall continue the flight under VFR and land as soon as practicable.

(c) IFR conditions. IF the failure occurs in IFR conditions, or if paragraph (b) of this section cannot be complied with, each pilot shall continue the flight according to the following:

(1) Route.
- (i) By the route assigned in the last ATC clearance received;
- (ii) If being radar vectored, by the direct route from the point of radio failure to the fix, route, or airway specified in the vector clearance;
- (iii) In the absence of an assigned route, by the route that ATC has advised may be expected in a further clearance; or
- (iv) In the absence of an assigned route or a route that ATC has advised may be expected in a further clearance, by the route filed in the flight plan.

(2) Altitude. At the highest of the following altitudes or flight levels for the route segment being flown:
- (i) The altitude or flight level assigned in the last ATC clearance received;
- (ii) The minimum altitude (converted, if appropriate, to minimum flight level as prescribed in paragraph 91.81(c)) for IFR operations; or
- (iii) The altitude or flight level ATC has advised may be expected in a further clearance.

(3) Leave clearance limit.
- (i) When the clearance limit is a fix from which an approach begins, commence descent or descent and approach as close as possible to the expect further clearance time if one has been received, or if one has not been received, as close as possible to the estimated time of arrival as calculated form the filed or amended (with ATC) estimated time en route.
- (ii) If the clearance limit is not a fix from which an approach begins, leave the clearance limit at the expect further clearance time if one has been received, or if none has been received, upon arrival over the clearance limit, and proceed to a fix from which

an approach begins and commence descent or descent and approach as close as possible to the estimated time of arrival as calculated from the filed or amended (with ATC) estimated time en route.

There are examples of *mission-critical* communication systems in the space industry that we may be able to apply to AHS.

The only examples of “critical” communication systems that we could find were in the space launch industry. Launch vehicle are equipped with radio communication systems that can trigger a self-destruct mode if a launch is aborted after takeoff. These systems are considered “mission-critical.” The military definition of “mission-critical” is not the same as the FAA’s “safety-critical” classification. The various requirements on reliability differ but are similar enough that AHS designers could possibly adopt some of the technologies and lessons learned.

Distribution of Responsibilities

Implications for AHS—An important implementation question for the AHS is what functions to have established in the roadway infrastructure and what functions to have resident on the vehicle.

***Lesson Learned*—There are a number of ways to distribute system functionality between the roadside and the vehicle. In aviation, the final authority for safe operation rests with the user.**

Related Issues from Air Traffic Control/Air Traffic Management—Air traffic controllers conduct the surveillance function, and it is their primary function to ensure separation standards are complied with by issuing instructions to pilots. The navigation function and actual avoidance of collisions with other aircraft is the primary responsibility of the pilot.

According to the Airman’s Information Manual, paragraph 407:

a. Pilot
   (1) When meteorological conditions permit, regardless of type of flight plan, whether or not under control of a radar facility, the pilot is responsible to see and avoid other traffic, terrain or obstacles.
b. Controller
   (1) Provides radar traffic information to radar identified aircraft operating outside positive control airspace on a workload permitting basis.
   (2) Issues a safety alert to an aircraft under his control if he is aware the aircraft is at an altitude believed to place the aircraft in unsafe proximity to terrain, obstructions or other aircraft.

The control of an air vehicle is clearly the responsibility of the operator. The commands issued by air traffic control are compulsory unless an emergency is declared. A similar functional distribution may be well suited for AHS.

Variations in Procedures

Implications for AHS—The manner in which AHS operations are instituted could vary across implementation sites (different regional, state systems); this can have an adverse effect on drivers and may limit system efficiency.

***Lessons Learned*—If it is intended that the AHS not have unique training requirements for usage, then it will be necessary to minimize the number and nature of any site-specific Standard Operating Procedures (SOP) across AHS implementations nation-wide.**

Related Issues from Air Traffic Control/Air Traffic Management—When a vehicle (aircraft or car) is produced, the manufacturer provides an operations manual. Most users comply with the basics of the infrastructure governing the use of the vehicle—rules of the road or federal aviation regulations for cars and aircraft, respectively. However, with fleet vehicles (truck fleets or airline aircraft), there can be an adoption of Standard Operating Procedures (SOPs) that adds a layer of complexity with following the basic infrastructure regulations. The SOPs are usually developed to either save operating cost by making operations more efficient or reduce the chance of human error by standardizing actions across all fleet operations personnel.

Another example of SOP development is that specific to operations in a certain area, such as approach paths to runways in areas where there are obstacles present (e.g., mountains or buildings). Accompanying the development and implementation of specific SOPs is some sort of unique training, or a specific briefing at a minimum. Chapter 5 on Standards Development discusses in more detail how SOPs are developed.

Minimum Equipment Lists (MELs)

Implications for AHS—The AHS will place some unique equipment requirements on the vehicle systems required for safe operations in an AHS. An identified minimum equipment set must be identified so that a vehicle can be assessed for compliance before authorization for AHS usage is given.

***Lessons Learned*—The most important point to note is that although the vehicle manufacturer must be involved in the development of an MEL, it is up to the operator, not the vehicle manufacturer, to comply with the minimum equipment set. This has significant implications with regard to product liability litigation.**

There are a number of means by which compliance with a functioning minimum equipment suite could be communicated to the AHS, such as standardized built-in-test (BIT), which transmits results to the roadway, or a discrete "check-in" process could be mandated so that all vehicles entering the AHS are given a diagnostic inspection before being admitted.

Related Issues from Air Traffic Control/Air Traffic Management—In the aircraft domain, it is interesting to note that the Federal Aviation Regulations governing the minimum equipment requirements exist in the regulations regarding *Operations* (FAR Part 121 and 135), not in the *Airworthiness Standards* (FAR Part 25); that is, the responsibility for ensuring compliance with minimum equipment capability lies with the operator, not the manufacturer. This has significant implications with regard to product liability litigation.

According to FAR 121.628, inoperable instruments and equipment.

(a) No person may take off an airplane with inoperable instruments of equipment installed unless the following conditions are met—
   (1) An approved Minimum Equipment List exists for that airplane.
   (2) The Flight Standards District Office having certification responsibility has issued the certificate holder operations specifications authorizing operations in accordance with an approved Minimum Equipment List. The flight crew shall have direct access at all times prior to flight to all of the information contained in the approved Minimum Equipment List through printed or other means approved by the Administrator in the certificate holder's operations specifications. An approved Minimum Equipment List, as authorized by the operations specifications, constitutes an approved change to the type design without re-certification.
   (3) The approved Minimum Equipment List must—
      (i) Be prepared in accordance with limitations specified in paragraph (b) of this section.
      (ii) Provide for the operation of the airplane with certain instruments and equipment in an inoperable condition.
   (4) Records identifying the inoperable instruments and equipment and the information required by paragraph (a)(3)(ii) of this section must be available to the pilot.

(5) The airplane is operated under all applicable conditions and limitations contained in the Minimum Equipment List and the operations specifications authorizing use of the Minimum Equipment List.

(b) The following instruments and equipment may not be included in the Minimum Equipment List—

(1) Instruments and equipment that are either specifically or otherwise required by the airworthiness requirement under which the airplane is type certificated and which are essential for safe operations under all operating conditions.

(2) Instruments and equipment required by an airworthiness directive to be in operable condition unless the airworthiness directive provides otherwise.

(3) Instruments and equipment required for specific operations by this part.

(c) Notwithstanding paragraphs (b)(1) and (b)(3) of this section, an airplane with inoperable instruments or equipment may be operated under a special flight permit under paragraphs 21.197 and 21.199 of this chapter.

Fail-Operational versus Fail-Passive

Implications for AHS—To safeguard the users of the AHS, the developers must consider the possibility of system-wide failure and the resulting return of control to the driver. Procedurally, the driver will be familiar with resuming vehicle control (upon exiting the AHS) in a certain, as yet to be determined, fashion. If the AHS automation were to fail, it would be important to provide some interim level of vehicle control until the driver “indicates” that they are ready to resume control. Without the exact procedure for resuming manual control defined, this is a very difficult discussion at other than a conceptual level.

***Lessons Learned*—If the AHS is designed to minimize the need for driver training, then it will be mandatory for the system to be Fail Operational to the extent it can remove a vehicle safely from the AHS and return control to the driver when the driver indicates a readiness to resume manual control.**

Related Issues from Air Traffic Control/Air Traffic Management—A system in the commercial transport environment with critical operational status is the Autoland system. The Autoland function is accomplished by the aircraft’s autopilot using a high-integrity navigation signal to guide the aircraft through the landing process, including approach guidance, runway alignment and flare, and rollout guidance. The autopilot must be Fail Operational to be certified for use. A Fail Operational system is one in which one or more failure(s) can occur but overall system integrity is still maintained. To achieve this requires that the guidance and control algorithms be hosted on three different processors that are linked together so the various position estimates and guidance commands can be compared one versus another. Each channel alone is capable of controlling the aircraft, but the triple redundancy allows for the continual cross-checking of performance. If there is significant disagreement among the three channels, the most discrepant channel is isolated and the other two continue to compare results. In this manner, a failure will be annunciated to the crew, but the process will continue to operate.

An alternative to the Fail Operational implementation is one that is Fail Passive. Fail Passive is used to describe the ability of a system to withstand a failure without endangering passenger safety and without producing excessive deviations from the flight path. A system that is Fail Passive usually consists of two channels. These two channels continually compare results. When the two channels don’t agree, the system annunciates a fault and, usually, control is returned to the operator.

Minimum Operation Performance Standards (MOPS)

Implications for AHS—The on-vehicle equipment to support AHS functions (headway and velocity regulation and lane tracking) will have to operate to a specified minimum performance level. The exact criteria can be described in terms of a position "error basket"; that is, tolerances for system performance in terms of lateral tracking and headway error, as well as velocity regulation.

***Lessons Learned*—If performance monitoring were part of the roadway infrastructure, the cost of instrumenting individual vehicles with specialized AHS equipment would be reduced by the cost of the BIT equipment (although redundancy, such as mentioned, could be achieved through a combination of built-in-test and roadway-based performance checking).**

Related Issues from Air Traffic Control/Air Traffic Management—There is a conversion going on in the performance tolerances of avionics in commercial aircraft. In the past, tests were performed to see if the equipment operated within specific tolerances to original specifications, such as acceptable deviation of a signal. Recently, however, there is a ground swell of system users who advocate performance description in terms of minimum performance with regard to positioning of the aircraft. This is a subtle distinction that warrants examination with regard to implementation in the AHS because of the different means for implementation. The "old" approach, checking for performance deviations beyond tolerances for various pieces of equipment, would necessitate BIT to warn of unreliable system performance. This places the burden of performance checking on the individual vehicles, either once at a "check-in" station or running as a background operation during AHS usage. An alternative is for the AHS roadway to identify vehicles that are not performing per positioning tolerances and remove those vehicles from the AHS.

Post AHS Capacity Limitations

Implications for AHS—The intent of an AHS is to increase roadway throughput, yet if there is no modification made to the termination egress of popular routes (e.g., downtown areas), then there may be a limitation to the throughput gain because the eventual destination is capacity-limited.

***Lessons Learned*—Driver aids in terms of enhanced or synthetic vision systems to help the driver see and avoid obstacles under periods of low visibility will mitigate the effect of low visibility on the driver's ability to resume control and exit the AHS.**

Related Issues from Air Traffic Control/Air Traffic Management—This is analogous to streamlining the en-route capacity of the National Airspace System (NAS) yet still being confronted with bottlenecks at the eventual destinations (terminal areas and the airports themselves). In a very real sense, the best approach to offloading efficient en-route highways or airways is to add more pavement at the destination. In the aviation environment, this means adding runways. It is important to note that parallel runways eliminate the need for coordinating crossing or intersecting runways, which present an inherent collision risk. There are standards for how close parallel runways can be and still support simultaneous parallel approaches; the obvious concern is adequate recovery time in case one of the aircraft on final "blunders" into the path of the other.

Another important consideration is the affect weather has on operations at a destination. In the aviation environment, low visibility has a profound effect on weather. In fact, the limitations on simultaneous parallel approaches are driven exclusively by visibility conditions. An airport like Minneapolis–St. Paul, which normally supports 60 takeoffs and landings per hour on two parallel runways, has its capacity cut in half when Instrument Meteorological Conditions exist. New Precision Monitoring Radar, which presents ATC personnel in the control tower with better resolution and faster updates, is being installed around the country to alleviate congestion due to blunder protection mandated under periods of low visibility.

When considering the AHS egress situation, the analogy from ATM breaks down because the driver of a car is autonomous; that is, they do not comply with commands from a routing authority. However, runway rollout and turnoff speed are indeed limiting capacity at some major airports today. The problem is especially profound in poor weather conditions. This will be an even larger problem for AHS. Any means by which additional traffic handling capacity can be added is sure to be the most efficient means by which egress congestion can be alleviated.

Evolution Toward a 4-D System

<u>Implications for AHS</u>—The issue of transition from current, non-automated highway usage, to an AHS must be considered carefully to ensure driver safety. There are two obvious approaches: (1) incremental automation, or (2) wholesale change to fully automated vehicle control. There are advantages and disadvantages to both implementation strategies. Incremental automation reduces the risk associated with the technical implementation because the system is not being required to handle all the different parameters (velocity and headway control as well as lateral control), yet when the full-up automated system is finally implemented, any given driver might revert back to "old" habits associated with a partially automated system. The wholesale change has the benefit of introducing a full-scale paradigm shift; the problem arises from the technical risk associated with trying to accomplish all functions with automation with initial entry into service.

***Lessons Learned*—All attempts at common "look and feel" between current and future systems should be a design goal.**

<u>Related Issues from Air Traffic Control/Air Traffic Management</u>—Currently, ATC commands are executed by pilots; there is no direct control of aircraft from the ground. The current implementation practice means that the flight crew is responsible for executing any instructions, either by manually flying the aircraft or by implementing changes to the autoflight system.

There may come a time when ATC will provide control instruction that will be "uploaded" directly into the autoflight system of the aircraft for direct execution. To keep some form of authority and responsibility with the flight crew, there may be a need for the crew to confirm the instruction and authorize the execution of the control instruction. If this scenario unfolds, there will exist two different "types" of ATC interaction: verbal instruction, flight crew action versus direct upload of information with flight crew confirmation and authorization. A flight crew could experience both types on a given flight if they fly from one national airspace (U.S.) to another (Mexico).

Introduction and Evolution of Autopilots

<u>Implications for AHS</u>—The AHS will provide the driver with the next step beyond cruise control because the system will most likely provide lateral control as well. If the AHS allows for decoupled control, either velocity or lateral control enabled individually without the other, the operating environment can be complicated in terms of conceptually tracking what the vehicle is doing. In addition to tactical command complexity (knowing what the automation is doing in terms of vehicle control at any given moment), there is a layer of complexity added when complex routes can be "strung together" to enable a route, including roadway transitions over longer distances.

***Lessons Learned*—Easy to understand control and display implementations are needed so that the current state of automated control is obvious to the user.**

Related Issues from Air Traffic Control/Air Traffic Management—The original autopilot functions were simply a wings-level sort of gyroscopic aid. This relieved the pilot from the tedium of dynamic control. Over time, “bank knobs” were implemented that allowed the pilot to initiate a turn. When the desired heading was turned to, the pilot would release the knob and the aircraft leveled out on the new desired heading. After a while, the same functionality was enabled in the vertical dimension, but the vertical dimension required some form of thrust control as well (an aircraft has to add power to climb and reduce power in a descent). The revolution in tactical (control of speed, heading, altitude, and vertical speed) aircraft control came about with the advent of the microprocessor. This technology enabled control panels that allowed pilots to discretely select values for speed, heading, altitude, and vertical speed. This reduced pilot workload because the pilot no longer had to closely monitor the active state of the aircraft when making a transition to a new heading, altitude, etc. The value could be selected and then executed with phenomenal reliability.

In the late 1970s, microprocessor technology was combined with mass storage of data to create the Flight Management System (FMS). The FMS allowed a series of tactical vectors (discrete speed, heading, altitude, or altitude transitions) to be strung together so that an entire flight could be “programmed” on the ground before the engines were even started. Operational problems have arisen with the FMS because the ATC environment is not static. Changes to the flight plan, particularly contingent changes (e.g., “Aircraft 101, climb to 10,000 *after* RISTI intersection”) require complicated interaction with the FMS.

It will be important to keep in mind the requirement for roadside intervention for a simple-to-use driver interface for the AHS.

If the preprogrammed route in an FMS is left undisturbed by the demands of ATC routing, the FMS is an enormous labor-saving device. If, on the other hand, ATC requires a number of changes to the original flight plan, then the FMS is more cumbersome than simply selecting discrete values for speed, heading, altitude, or altitude transitions with a conventional autopilot. It will be important to keep the intervention requirement in mind for a simple-to-use driver interface for the AHS.

Vehicle-to-Vehicle Communications (TCAS II)

Implications for AHS—The implementation scheme for the AHS has not been determined, but the requirement of collision avoidance may generate the need for intervehicle communication. The reason this communication would aid the collision avoidance function is that a lead car could communicate to those following what its intent is (e.g., that a slowdown maneuver is about to commence). This would save the lag that would be incurred if the message had to be *linked* to following cars through the roadside and would also save the lag incurred if the following cars had to *sense* the velocity change of the lead car.

Lessons Learned**—The integration of a vehicle-to-vehicle communication function for collision avoidance must be implemented in such a manner as to be compatible with the system-wide maneuvering of vehicles. The collision avoidance maneuver must specifically be coordinated with any centralized control function for an AHS.**

Related Issues from Air Traffic Control/Air Traffic Management—This approach is not unprecedented. In response to calls for increased protection from midair collisions, the commercial aviation industry developed a transponder-based interrogation and reporting system that provides pilots with information regarding the relative positions of other “participating” aircraft in the vicinity. Paths are projected based upon current trajectories, with the point of closest approach being closely monitored. If the point of closest approach is within a specified "sphere," an alert will first identify the situation and then, if closure continues, provide evasive maneuvering guidance in the form of a vertical maneuver (see Figure 17).

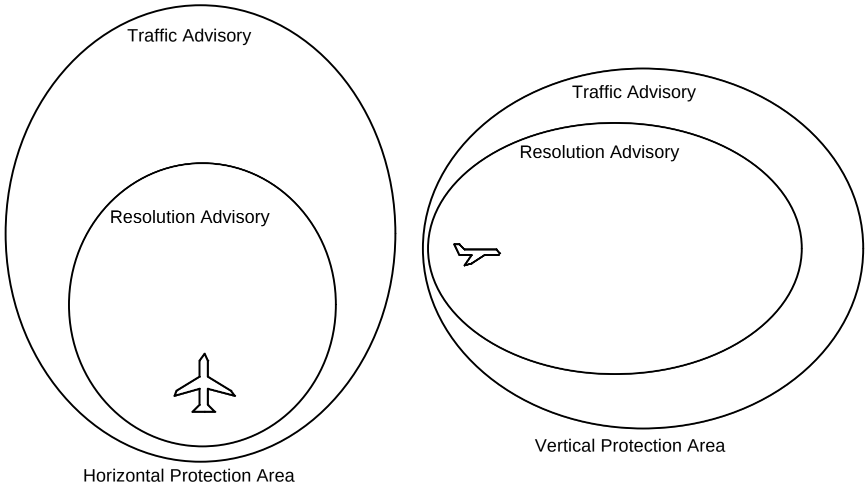


Figure 17. Graphic Depiction of Protected Airspace

> The TCAS equipment in the aircraft interrogates air traffic control transponders on aircraft in its vicinity and listens for the transponder replies. By computer analysis of these replies, the airborne TCAS equipment determines which aircraft represent potential collision threats and provides appropriate display indications (or advisories) to the flight crew to assure separation. (p. 2, RTCA/DO-185)

There are two levels of alert in the current TCAS II system: Traffic Advisory and Resolution Advisory. The Traffic Advisory, or TA, energizes a display that shows the relative positions of “other” aircraft, while the Resolution Advisory, or RA, provides the pilot with vertical guidance for an evasive maneuver.

> If the threat detection logic in the TCAS computer determines that a proximate aircraft represents a potential collision or near-miss encounter, the computer threat resolution logic determines the appropriate vertical maneuver is one that ensures adequate vertical separation while causing the least deviation of the TCAS aircraft from its current vertical rate. (p. 2, RTCA/DO-185)

The following figure reflects the modification to alert time that is dependent on altitude. The modification is dictated by the requirement for more time required for maneuvering at higher speeds (highly correlated with altitude). Simply speaking, the faster one is traveling the more lead time is required for notification of impending disaster so that an avoidance maneuver can be successfully completed.

Own Altitude (in ft., Std day)	**Radar Altitude**		**Pressure Altitude**			
	Up to 500	500D 2500	Up to 10,000	10,000D 20,000	20,000D 30,000	Above 30,000
Alarm Time (sec)	Inhibit	20	25	30	35	35

Figure 18. Altitude Dependent Alert Warning Time

The cockpit TCAS display, shown in the Figure 19, utilizes shape and color coding to aid in the discrimination of target interpretation between TA and RA threats.

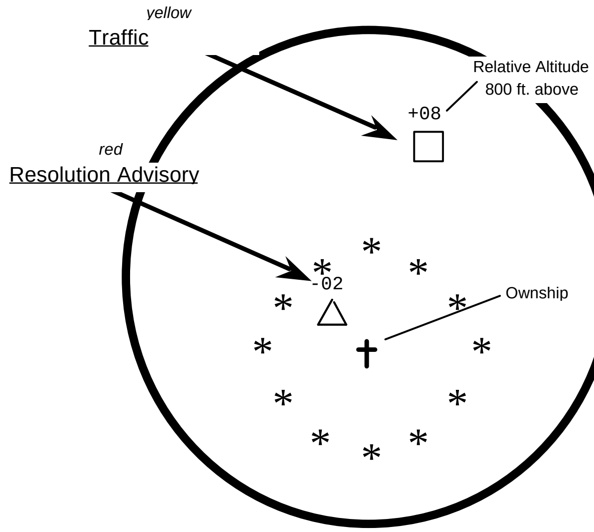


Figure 19. TCAS Cockpit Display

TCAS has been met with controversy. While flight crews believe it aids in their ability to “see and avoid” traffic conflicts, ATC personnel firmly believe that TCAS contributes to the problem of separation standard violation (cf. the television show “Dateline,” broadcast 7/14/94). Pilots are trained to respond to the Resolution Advisories independent of previous ATC clearance. The controllers fear that pilots responding to a Resolution Advisory may in fact cause a traffic conflict because they violate the clearance given by the controller.

SELECTED INSTITUTIONAL ISSUES

There are a number of issues associated with the implementation of a nation-wide system so that the procedures one goes through to gain admittance to an AHS are similar regardless of location. Although it was outside the scope of this contract effort to address specifically institutional issues, two issues are included here because of their importance in the Air Traffic Management world today and their direct applicability to AHS.

Institutional Issues

- Avoiding system fragmentation
- A national AHS (interjurisdictional •issues)

Avoiding System Fragmentation

Implications for AHS—The standards for the AHS are likely to be developed and regulated by the Federal Government, but the actual procurement and operation of roadside hardware will be done by local authorities. It will be important for standards to be established that allow agencies, at the state or metropolitan level, to acquire and operate hardware that is compatible system wide.

***Lessons Learned*—Either national standards or mandated agreements between adjacent AHS control centers are required for “seamless” operations.**

Related Issues from Air Traffic Control/Air Traffic Management—In the aerospace industry, there are organizations that serve the role of a clearinghouse for electronic standards so that consumers (airlines, corporate aviation, and the individual pilot) can buy components (Line Replaceable Units) from different vendors that adhere to specific standards and be assured they will work in their aircraft. The development of standards is getting to be a much more important activity with the integration of air traffic control and aircraft. The concept of air traffic management (ATM) is for controllers to issue specific required time of arrivals to expedite traffic flow. The smooth flow of instructions, using a non-verbal digital data link, can only be accomplished with a previously agreed to communication protocol. In the aviation environment, that means that the standards for communication have to be consistent within the NAS for the various control centers (control tower, approach and departure, and en-route centers) as well as internationally, so our aircraft can operate within their control environments. It is this last category, international usage, that most closely resembles the dilemma facing bordering regulatory authorities as they attempt to create a "seamless" AHS boundary between their systems.

Standards development, not technology development, is today's main hurdle in improving the ATM system.

One clear lesson from aviation is that technology is no longer the stumbling block. What slows progress is the necessary and time-consuming process of building interjurisdictional consensus on the standards and procedures that will be followed when using the new technologies.

A National AHS (interjurisdictional issues)

Implications for AHS—Similar to the issues of collaborative hardware between AHS jurisdictional boundaries, there is an issue of honesty with regards to day-to-day operations and the handling of traffic flows between adjacent AHS systems.

Lessons Learned—**Adjacent AHS control centers must be honest with one another in terms of allowing incoming traffic, up to capacity handling.**

Related Issues from Air Traffic Control/Air Traffic Management—In the NAS there is a specific protocol for agreeing upon the procedures for traffic hand-offs between adjacent control sectors. It is acknowledged that air traffic flow changes; in general, traffic is increasing, but there are ebbs with seasonal demands. The FAA has a policy to establish Memorandums of Agreement (MoA) between adjacent control sectors so that the procedures for traffic hand-off, traffic rates (and interaircraft spacing), and unusual routing requests (direct, great circle route clearances) are mutually agreed upon and clearly defined for implementation by the controllers at the two facilities.

Key to the future of ATM (and AHS) will be reliable, and honest, two-way communication. (11)

Although there is an established traffic flow agreed to in the MoA, the controllers at a center can claim that adverse weather in their area is negatively affecting their ability to accept hand-offs from adjacent sectors. (The biggest impact on a center's ability to handle traffic is local weather.) The restriction of traffic entering the afflicted center has an effect that ripples back through the adjacent centers and their ability to handle incoming traffic; in terms of constraining traffic flow, it becomes a domino effect.

SELECTED TECHNOLOGICAL ISSUES

The following purely technological issues are discussed next

Technological Issues

´ Mode annunciation standardization
´ Designing for diagnosis
´ Handling inclement weather
´ Lane changing

Mode Annunciation Standardization

***Lessons Learned*—The driver interface for AHS control should be standardized so that the driver would see the same conventions for the AHS interface in the vehicle in terms of location-color-text messages.**

Implications for AHS—For the driver to understand the current state of automated operation (“On” or “Off”) and to have confidence in reliable system operation, it will be essential that automation status be presented in a clear, unambiguous fashion.

Related Issues from Air Traffic Control/Air Traffic Management—In commercial transport aircraft, most systems are developed according to an agreed-upon standard so that there is good inter-operability between aircraft types; that means that an airline doesn’t need to specialize the pilots into Boeing-only versus Douglas-only groups. Each aircraft has unique considerations that require some amount of specialized (“type rating”) training, but for the most part, a pilot can hop into any aircraft and manually fly the vehicle. This is not necessarily the case when it comes to using the autopilot and autothrottle functions in aircraft. There has been an evolutionary addition of features to the basic aircraft until we have the sophisticated path control hardware outlined below.

The biggest problem is a lack of standards for the use of location, color, and text messages in Flight Mode Annunciation.

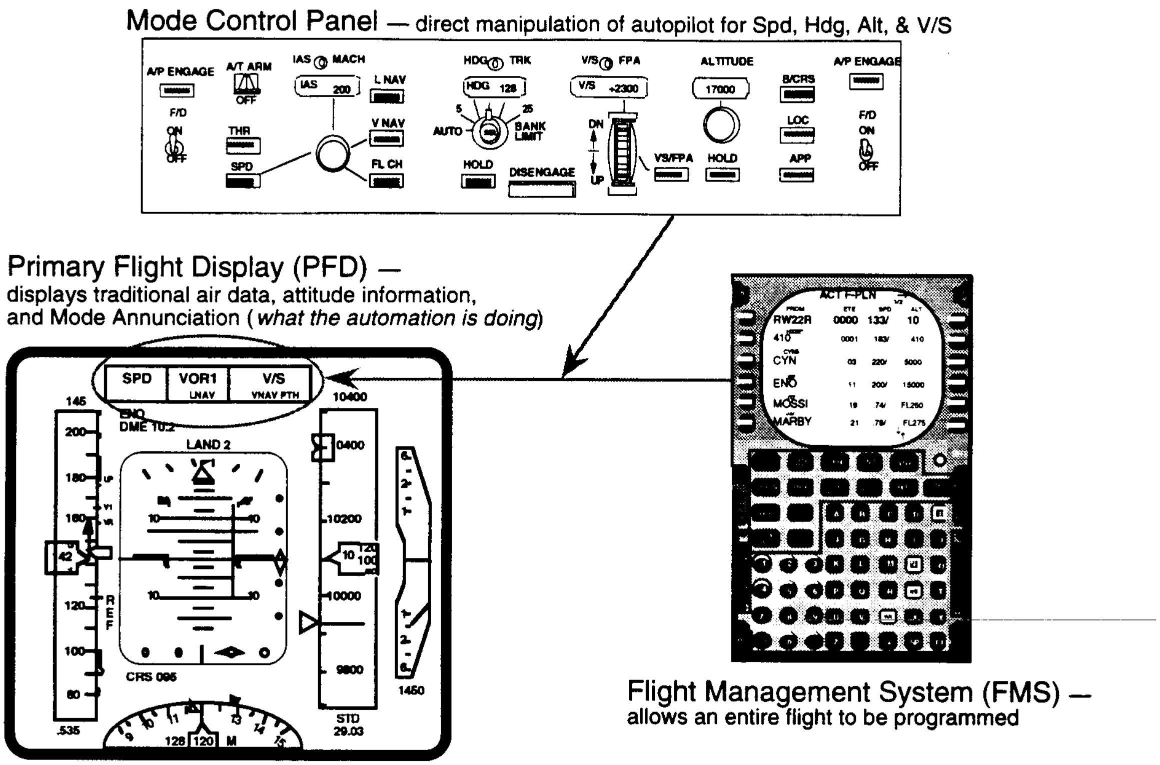


Figure 20. Example of Mode Annunciation in Commercial Aircraft

Airlines used to request “specialized” features, citing specialized operational needs and competitive edge as the reason. Today, airlines are asking for their fleets to be retrofitted with one *standardized* avionics suite. The reasons are twofold—the cost of training and the cost of maintaining the specialized equipment.

Designing for Diagnosis

Implications for AHS—The ability for the driver to understand the “health” of the AHS, particularly their own vehicle’s automated system, is an issue for AHS designers. There are two philosophies that can be adopted for AHS implementation: (1) advise the driver of system integrity and failure in anticipation of their resuming control, or (2) automatically transition a malfunctioning vehicle from the AHS, anticipating that the driver can regain manual control in a timely fashion.

***Lessons Learned*—System status should be presented to the user in an unambiguous manner.**

Related Issues from Air Traffic Control/Air Traffic Management—In commercial aviation, the pilot is responsible for safe operations, which mandates a design philosophy of always informing the crew of system status. There are flight phases, takeoff and landing, when noncritical information is inhibited. This is recommended for AHS as well—inhibit nonessential annunciation of information to the driver during periods of high workload (e.g., entry, exit, and lane changing).

Handling Inclement Weather

Implications for AHS—As mentioned in a previous section (Post AHS Capacity Limitations) inclement weather, specifically low visibility, has a profound effect on system throughput if the user is tasked with "seeing and avoiding" obstacles.

The Autoland system operates in a manner identical to the AHS; that is, the vehicle maintains velocity and guidance without any input from the user.

Related Issues from Air Traffic Control/Air Traffic Management—Forecast visibility for the destination airport is a vital part of a weather report or briefing. Cloud ceiling and visibility along the runway (termed runway visual range—RVR) are important due to mandated equipment (both ground-based and aircraft navigation aids) and training required for low-visibility approaches. After ascertaining the weather conditions, the pilot can determine what sort of "rules" the flight will operate under: Visual Flight Rules (VFR) or Instrument Flight Rules (IFR).

***Lessons Learned*—The problem with Autoland is the very real possibility that after the successful landing, the pilot may *not* be able to see to taxi the aircraft off the runway! The alternative technology of enhanced or synthetic vision may be perfectly suited to providing low-visibility navigation capability to avoid bottlenecks at the egress of the AHS.**

Because of the requirement to have contact with the ground visually, the most germane of the weather restrictions comes into play in terms of landing operations. Both the flight crew and aircraft must be certified to specific performance criteria (Categories or CAT).

There are a number of technology implementations to overcome conditions of low or no visibility (CAT IIIc). The most widely implemented is an Autoland function. Utilizing the Instrument Landing System lateral (Localizer) and vertical (Glideslope) guidance signals, the aircraft autopilot is used to fly the approach, flare the aircraft over the ground, touch down, and maintain centerline on the rollout. Specific criteria are established with which all Autoland systems must show compliance.

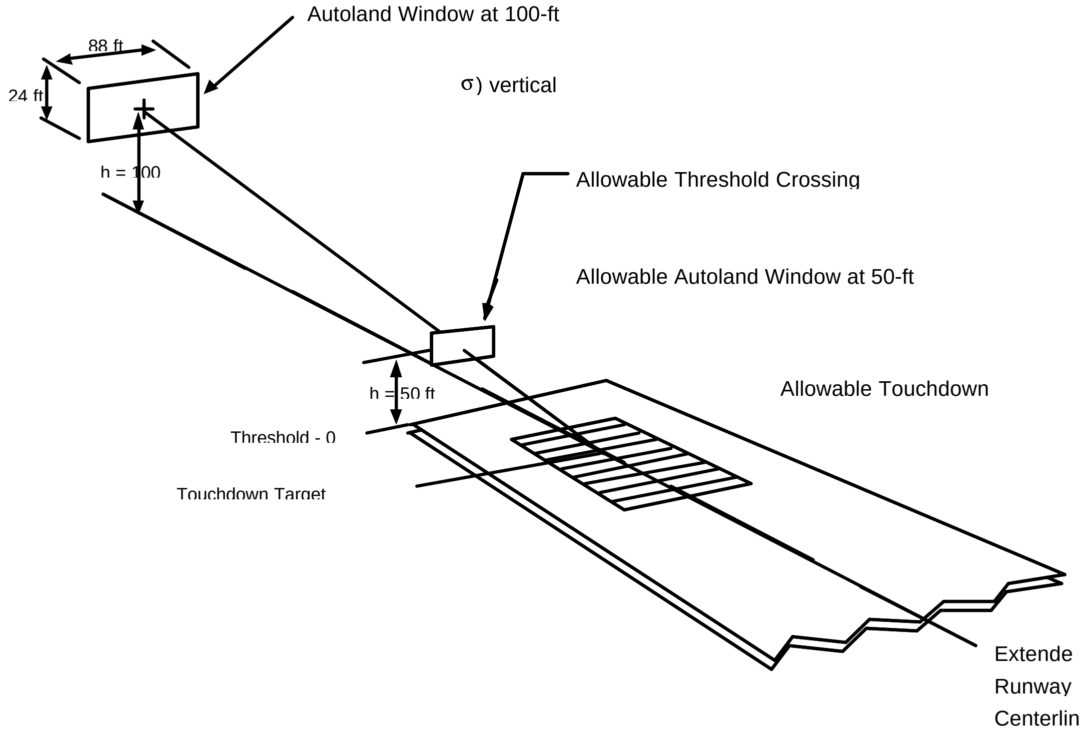


Figure 21. Autoland Criteria from FAA Advisory Circular 20-57A

To avoid inhibiting AHS system performance to the "least common denominator," we recommend type-rating vehicles based on the on-board equipment. In this way, for example, commercial vehicles could continue to use AHS in poor weather conditions if the vehicles were so rated, while personal vehicle operators without the proper rating would be prohibited.

The biggest drawback to the Autoland system is the Fail Operational requirement, which imposes added cost to the high-integrity system (this subject was addressed in a previous section entitled Fail-Operational versus Fail-Passive)

Another technical resource brought to bear on the low-visibility landing problem is that of imaging sensors. Forward-looking infrared (FLIR) technology has been employed by the military to obtain "first look–first shot" capability at night and under conditions of low visibility for years. FLIR and millimeter-wave radar are both viable technologies for presenting a real-time image of the forward scene, and in fact are being used by Northwest Airlines to equip their DC-10 and B-747 fleet to land under CAT IIIb conditions. Northwest plans to present the view from the imaging sensor on a Head-Up Display to aid the pilots in acquiring the landing environment.

Lane Changing

Implications for AHS—There are two issues for AHS: (1) entry/exit from AHS, namely the transition from manual to automated control and back; and (2) transition between automated lanes.

The entry/exit implementation has a number of scenarios being put forth at this time. These range from "check-in" areas in which the integrity of the vehicle automation is ensured before automatic control will accelerate the vehicle into the AHS designated lanes. A less elaborate scheme is the "merge on the fly." In this scheme, integrity assurance is achieved dynamically (presumably a continuous background operation while the vehicle is using the AHS), and the AHS merges the vehicle into the automated lane when spacing conditions are met.

The technical implementation issues associated with transition between automated lanes are not nearly as complicated as the transition between manual and automated lanes. There is, however, a point to be made in terms of efficiency with multiple automated lanes. If the left-most lane is reserved for long-distance travel (the concept of "long distance" is relative to the journey length of all the vehicles using the system for a given segment length), then minimal perturbations to speed can be achieved, which by definition is a more efficient means of operation.

***Lessons Learned*—Fuel efficiency can in fact be a goal for lane selection in a multilane AHS. If there are multiple lanes, the left-most lane can be restricted in terms of the number of entries or exits per unit of distance to reduce the number of speed fluctuations.**

Related Issues from Air Traffic Control/Air Traffic Management—There are two analog situations from the aviation world. One is a lateral routing change; the other is an altitude change. Both accomplish a similar function to lane transitions in AHS, namely, more efficient operations in terms of fuel efficiency and increasing overall system capacity (traffic management).

In terms of lateral routing, pilots are always seeking more direct routes. Newer aircraft with sophisticated navigation equipment INS or GPS are seeking great circle routes, which tend to take them off the established airway network, thereby complicating ATC's ability to predict downstream conflicts. In addition, severe weather warrants routing changes to avoid unsafe flight conditions.

There are two primary reasons that a flight crew will seek an altitude change: (1) comfort (to avoid turbulence), and (2) fuel efficiency (generally speaking, the higher an aircraft flies, the more efficiently it operates). It is assumed that there will not be a qualitative difference of lane smoothness in the AHS, so ride quality is a nonissue.

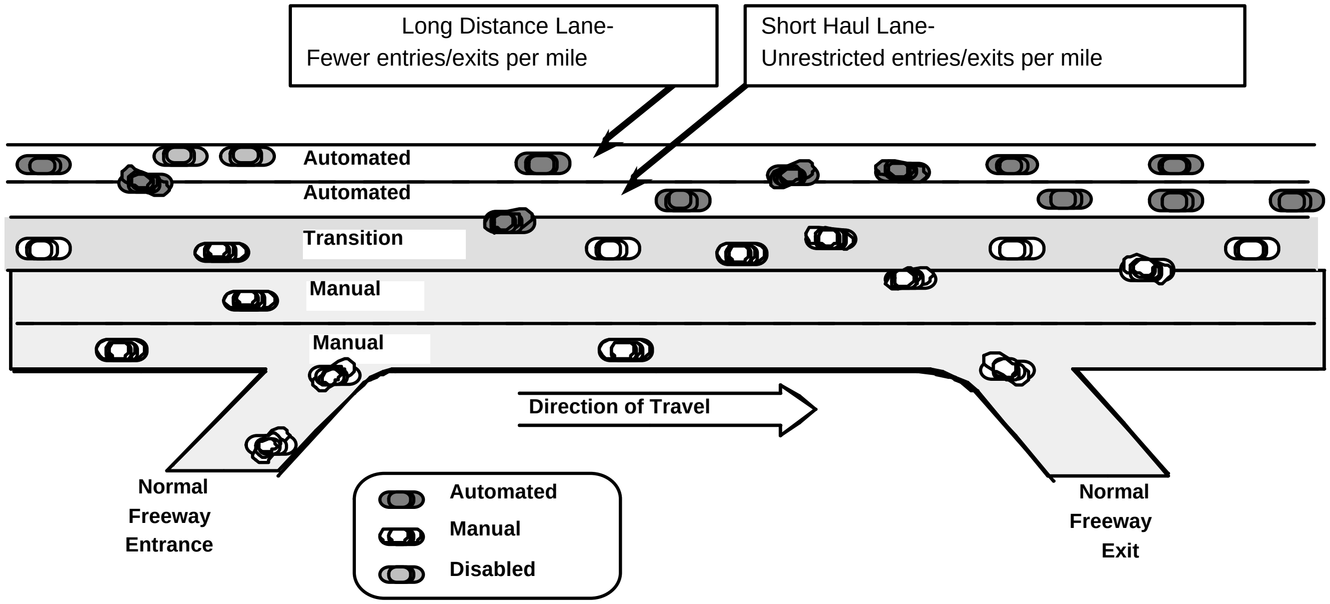


Figure 22. Multiple Automated Lanes in an AHS

CHAPTER 5: STANDARDS DEVELOPMENT IN THE U.S. NATIONAL AIRSPACE SYSTEM

Many different standards have been developed to permit the National Airspace System to operate. Those standards that relate to the air traffic control system's primary function, the safe separation of participating aircraft, are discussed in this chapter. Two kinds of standards are discussed:

- Equipment standards (subsystem accuracies and performance requirements)
- Operational standards

Relevant AHS parallels and Lessons Learned are called out in sidebars. The chapter concludes with applications to and recommendations for developing standards for an AHS.

EQUIPMENT STANDARDS

Two general classifications of standards are utilized within the National Airspace System. The first defines accuracy standards for communication and navigation equipment located both on the ground and in aircraft and performance standards for air traffic control equipment such as radar surveillance and communications equipment. In general, these standards are promulgated by the FAA and are based upon the performance of both research and prototype equipment. In general, when developing equipment specifications for ground-based navigation or surveillance equipment, the FAA issues general design specifications.

Historically, performance and accuracy standards were backwards engineered from the capability of available technology.

Once the equipment is procured and installed, its accuracy is measured. Based upon observed results, the equipment may be modified and/or improved, with the results becoming the new standard for that type of equipment. As the specific technology matures and operational improvements are made, tolerances are reduced and accuracy standards are increased.

Although somewhat archaic sounding, this methodology was understandable when one considers the state of the art when most existing FAA navigation and surveillance equipment was first developed. The specifications for the current international standard aviation navigation system, VORTAC, were initially prepared by the FAA's predecessor in 1937. The current standard instrument landing system (ILS) was first demonstrated by the Federal Government in 1929. Until the 1990s, most of the surveillance equipment used by the FAA had basically been designed during World War II. Many of the communications transmitters utilized by the FAA still bear the nameplate of its predecessor, which was absorbed by the FAA in 1958.

The trend today is toward defining performance standards that are independent of specific technologies.

The lead time to develop new equipment, in conjunction with government procurement inefficiencies, make it likely that the time lag between system specification and installation can be well over a decade. This makes it difficult to define rigid specifications that will most likely be obsolete before they can be implemented. The FAA is moving toward defining general specifications or permitting the private sector to design equipment that meets general system specifications.

In the past, some specifications have been worked out jointly with the Radio Technical Commission for Aeronautics (RTCA) and Aeronautical Radio Inc. (ARINC) prior to the FAA setting specifications. It appears that this cooperative trend will continue and possibly expand.

Ground-Based versus Airborne Equipment Standards

The FAA has the unique role of being the regulatory agency for the very equipment they own and operate. Many claim it is too difficult to maintain the necessary objectivity.

The FAA is normally the prime contractor for ground-based Air Traffic Control equipment. As the sole user of this equipment, the FAA develops both design and operational standards, contracts for development and installation, and eventually becomes the operator of the procured equipment. Due to the nature of the FAA's mission and the uniqueness of the equipment to be developed, the development process is usually individualized for each particular project. This differs from the development of airborne equipment, since there will most likely be many manufacturers and users.

Once the ground-based systems have been developed, the FAA controls the accuracy of airborne navigation equipment through the issuance of Technical Standard Orders (TSO). This procedure is designed to ensure that airborne equipment operates properly in conjunction with the ground-based navigation and communication equipment.

TSOs ensure that manufacturer equipment is compatible with the FAA-owned and -operated ground-based equipment.

TSOs are rigid specifications provided to equipment and aircraft manufacturers. The FAA requires that all navigation and communication equipment installed in an aircraft conform with appropriate TSOs. As the capability and accuracy of ground-based transmitters increases, the FAA issues new TSOs with more rigid requirements. The new TSO typically includes a time-limited clause that permits the use of previously approved equipment for a specified time period.

The Development Process

More recent developments in ground-based ATC systems follow a more systematic, analytical process. The steps vary somewhat due to each project's unique needs. The following discussion demonstrates the general process.

The Conceptual Stage—An engineering and systems analysis study is initially conducted by either the FAA, industry contractors, and/or universities. The parameters included in this study are based upon the eventual use of the system and its desired performance. Only very broad performance standards are initially developed. If the system under study is a replacement/upgrade of existing systems, this study identifies and analyzes existing system problems and identifies possible improvements. If it is a new system, the study defines general needs and overall reliability requirements. The study concentrates on overall system parameters such as performance, system interfaces, and coordination with other regulatory agencies such as the Federal Communications Commission, the National Weather Service, and the Department of Defense. General operating characteristics and requirements such as accuracy requirements, reliability standards, operating frequencies, bandwidths, and generalized user needs are defined as part of this study. Elementary cost benefit and preliminary human factors studies are also conducted as part of this study.

General standards are established and used to evaluate alternative system configurations.

This analysis explores and sets general standards in the following areas: services, system operation, standardization, and evaluation. In general, some of the following criteria are used to compare alternative system configurations.

Services

_ Necessary service should be provided to meet the needs of the military and civil communities.
_ At a minimum, services sufficient to allow safe transportation should be provided.
_ To the extent possible and consistent with cost-effectiveness, services that benefit the economy should be provided.

System Operation

_ Systems should be responsive and flexible to changing operational and technological environments.
_ Modification and transition of systems should occur in an orderly manner to accommodate technical improvements.
_ Systems should be provided to a variety of user classes with the minimum number of subsystems.
_ Services should be provided in all relevant operating areas.
_ Research and introduction of new systems and concepts should be considered, particularly where requirements or cost savings are not met.

Standardization

_ A necessary degree of standardization and interoperability should be recognized and accommodated for both domestic and foreign operations.
_ Navigation services and systems should be technically and politically acceptable to diverse groups, including NATO and other allies, the International Civil Aviation Organization (ICAO), and IMO.
_ The basic capabilities to permit common use and common operational procedures by civil and military users should be provided.
_ Civil and military navigation equipment should be compatible to the extent feasible.

Evaluation

_ Evaluation of the acceptable level of safety risks to the Government, user, and general public as a function of the service provided.
_ Evaluation of the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the service desired measured against the benefits obtained.
_ Evaluation of the total cost impact of any government decision on system users.

The lack of end-user involvement early on in development programs has been cited as the reason for several unsuccessful FAA programs.

Once these developmental criteria have been defined, the FAA meets with appropriate user groups such as air traffic controllers, ARINC, RTCA, and other representative user groups to determine how the proposed system might be utilized by each group. Some of the factors considered include:

_ Vehicle speed, size, and maneuverability
_ Regulated and unregulated traffic flow
_ User skill and workload
_ Processing and display requirements for navigational information

For most users, cost is generally the driving consideration. The price users are willing to pay for equipment is influenced by the activity of the user: air carrier, air taxi, general aviation, helicopters, etc.

_ Environmental constraints; e.g., weather, terrain, man-made obstructions
_ Operational constraints inherent to the system

- Economic benefits
- Vehicle performance variables such as fuel consumption, operating costs, and cargo value
- Cost/performance tradeoffs of equipment

Multiple contractors develop concepts independently.

Preliminary system performance requirements are defined by the FAA within this framework. The FAA then employs three or four different contractors to develop engineering models of prototype systems. These proof-of-concept studies do not normally include fully operational prototype systems, but normally employ computer modeling, mini-system tests, and/or critical subsystem, breadboard-level prototypes.

The Design Evaluation Process—Every new system proposal is unique and different, but the contracts issued by the FAA generally utilize criteria promulgated in the Federal Radionavigation Plan, prepared jointly by the Departments of Defense and Transportation. The Federal Radionavigation Plan is published to provide information on the management of those federally provided radionavigation systems used by both the military and civil sectors. It supports the planning, programming, and implementing of air, marine, land, and space navigation systems to meet the requirements shown in the president's budget submission to Congress. This plan is the official source of radionavigation policy and planning for the Federal Government and has been prepared with the assistance of other government agencies.

General system criteria are defined in the Federal Radionavigation Plan prepared jointly by the DOT and DOD.

Every new contract proposal is unique, but the Federal Radionavigation Plan includes general criteria that the system design should meet and serves as an evaluation guide for the FAA. The radionavigation plan includes the following criteria that can be used for later system evaluation. All the criteria listed below are applicable to AHS equipment.

Criteria

- The system must be suitable for use in all aircraft types that may require the service without limiting the performance characteristics or utility of those aircraft types; e.g., maneuverability and fuel economy.

Replace the words *pilot* with *driver* and *aircraft* with *vehicle*, for example, and most of the criteria listed here will apply to AHS-type equipment.

- The system must be safe, reliable, and available; and appropriate elements must be capable of providing service over all the used airspace of the world, regardless of time, weather, terrain, and propagation anomalies.
- The integrity of the system, including the presentation of information in the cockpit, shall be as near 100% as is achievable and, to the extent feasible, should provide flight deck warnings in the event of failure, malfunction, or interruption.
- The system must have a capability of recovering from a temporary loss of signal in such a manner that the correct current position will be indicated without the need for complete resetting.
- The system must automatically present to the pilot adequate warning in case of malfunctioning of either the airborne or source element of the system. It must ensure ready identification of erroneous information that may result from a malfunctioning of the whole system and, if possible, from an incorrect setting.
- The system must provide in itself maximum practicable protection against the possibility of input blunder, incorrect setting, or misinterpretation of output data.

_ The system must provide adequate means for the pilot to check the accuracy of airborne equipment.
_ The system must provide information indications which automatically and radically change the character of its indication in case a divergence from accuracy occurs outside safe tolerance.
_ The system signal source element must provide timely and positive indication of malfunction.
_ The navigational information provided by the system must be free from unresolved ambiguities of operational significance.
_ Any source-referenced element of the total system shall be capable of providing operationally acceptable navigational information simultaneously and instantaneously to all aircraft that require it within the area of coverage.
_ In conjunction with other flight instruments, the system must in all circumstances provide information to the pilot and aircraft system for performance of the following functions:
  - Continuous tracking guidance
  - Continuous determination of distance along track
  - Continuous determination of position of aircraft
  - Position reporting
  - Manual or automatic flight
• The information provided by the system must permit the design of indicators and controls that can be directly interpreted or operated by the pilot at his normal station aboard the aircraft.
_ The system must be capable of being integrated into the overall ATC system (communications, surveillance, and navigation).
_ The system should be capable of integration with all phases of flight, including the precision approach and landing system. It should provide for transition from long-range (transoceanic) flight to short-range (domestic) flight with minimum impact on cockpit procedures/displays and workload.
_ The system must permit the pilot to determine the position of the aircraft with accuracy and frequency that will (a) ensure that the separation minima used can be maintained at all times, (b) execute properly the required holding and approach patterns, and (c) maintain the aircraft within the area allotted to the procedures.

_ The system must permit the establishment and the servicing of any practical defined system of routes for the appropriate phases of flight.

_ The system must have sufficient flexibility to permit changes to be made to the system of routes and siting of holding patterns without imposing unreasonable inconvenience or cost to the providers and the users of the system.

_ The system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.

_ The system must be cost-effective to both the Government and the users.

_ The system must employ equipment to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installation in aircraft or on the ground.

- The system must be free from signal fades or other propagation anomalies within the operating area.
- The system avionics must be comprised of the minimum number of elements that are simple enough to meet, economically and practically, the most elementary requirements, yet be capable of meeting, by the addition of suitable elements, the most complex requirements.
- The system must be capable of furnishing reduced service to aircraft with limited or partially inoperative equipment.
- The system must be capable of integration with the flight control system of the aircraft to provide automatic tracking.
- The system must be able to provide indication of a failure or out-of-tolerance condition of the system within 10 seconds of occurrence during a nonprecision approach.

The FAA's hierarchy of selection criteria normally gives precedence to system safety, reliability, and then cost.

The Operational Evaluation—Once the contractor proposals are completed, the FAA conducts a detailed evaluation, using the predefined criteria, then normally selects two contractors to develop and deliver prototype systems. When the prototype systems are delivered, the winning design is selected based upon the previously defined criteria. The FAA overall decision is made based upon how well the prototype system meets or exceeds the evaluation criteria. The FAA's hierarchy of criteria normally gives precedence to system safety, reliability, then cost. If both systems are determined to be compatible and essentially provide the same service, it is possible for both systems to be selected.

Since the FAA is normally the prime bidder and operator, once a standard is selected, an equipment procurement bid will be announced, with all interested manufacturers eligible to bid. The manufacturer will be selected based upon not only cost, but manufacturer's expertise and reliability and past performance.

If the equipment to be procured might be sold to agencies other than the FAA, other countries, or private operators, the winning standard will be publicly announced and all contractors will be made eligible to build equipment.

OPERATIONAL STANDARDS

It is the pilot's responsibility to accurately navigate the aircraft. The air traffic control system's primary purpose is to provide safe separation of aircraft and provide a redundant method of detecting and correcting anomalous behaviors, determine appropriate corrective actions, communicate these actions to the pilot or aircraft, and allow time for the aircraft to return to its proper flight path.

We will use the standards governing the safe separation criteria for aircraft as a case study of how operational standards are developed within the National Airspace System.

Historical Methodologies for Operational Standards Development

Historically, operational standards have been developed empirically through trial and error.

Until recently, no universally accepted standard method of establishing separation criteria in the air traffic control system existed. Current operational separation standards were derived empirically through the synthesis of controller experience, observed navigation deviations, pilot-reported problems, and system-reported errors. Trial and error, combined with rigorous investigation of all system failures, have resulted in the implementation of separation criteria that permit safe operation in the airspace system.

The trend today is toward a more theoretical analysis of the needs of the users and requirements of the system.

The proliferation of new technologies and techniques will not permit such a cavalier approach to separation, however, and new theoretical methodologies for the development of standardized methods are being developed and implemented. These are discussed later in this chapter.

An integrated navigation/air traffic control system, known as the National Airspace System, was not truly needed nor developed until the late 1930s. Until that time, very little organized commercial aviation existed within this country. The early airlines primarily carried mail, and those that carried passengers normally did so during daylight periods of good weather where navigation and traffic separation tasks could be accomplished visually. The onset of World War II and the resultant increase in high-priority, fairly complex aircraft operations spurred the development of a unified method of aircraft navigation and air traffic control.

Most early system standards developed empirically, utilizing observations and operational experience. If a procedure or piece of equipment proved fairly reliable, it soon became the standard and was then refined and improved. No systematic means of predicting results and probability assessment were conducted. Imprecise performance measurements, limited understanding of the variables, and an inability to predict all possible variances limited early system planners' efforts in this area. Adding capacity to the system was accomplished empirically, using the knowledge and experience gained by the air traffic controllers.

Operational standards, as with equipment standards, have been developed empirically.

If, for example, traffic dictated that a new airway be created parallel to an existing airway, the airway specialist charged with developing and plotting new airways would consult with air traffic controllers familiar with the operational area. Utilizing the controllers' experience, specialists could predict normal flight deviations from the centerline of the existing airway. It could reasonably be assumed that flight deviations on the new airway would be similar in magnitude and frequency. To provide adequate separation between the two airways, a minimum distance of twice the maximum observed variance was required. This would then become the minimum standard distance permitted between the two airways. Usually, additional distance would be added as a safety margin.

This methodology only took into account "normal" deviations from the airway. Normal deviations were those expected due to navigation transmitter and receiver error, routine course deviations, and corrections performed by the pilot. In general, these errors tend to form a Gaussian distribution. The principal problem with this type of separation analysis is that the statistics of aircraft position displacement are easy to predict within two to three standard deviations of the mean, but the tails of the probability curves are difficult to predict.

Analyzing operational deviations using statistical methods fail due to the one-of-a-kind nature of most incidents.

Gross navigational and operational deviations by the pilot (known as aircraft wander or pilot blunders) cannot be reliably modeled nor predicted realistically. They are one-of-a-kind incidents with little statistical probability of occurring again in the future. A navigational blunder typically prompts an investigation and corrective action is taken, but this only serves to fix that particular situation. Certain generalizations about that particular incident may be applied to the entire air traffic control system.

Data reporting, collection, and analysis of *incidents* is crucial to the continued development and refinement of operational standards. An exemplary system is the anonymous Accident Reporting System (ARS) used by the FAA.

These gross navigational variances are by their very nature hard to predict and are in fact the most critical of flight errors, since they are the most unpredictable. Various reporting methods, such as pilot reports, anonymous reporting systems and computer monitoring equipment are currently utilized to identify potential areas of operational concern. It is hoped that some of these can be prevented through systematic evaluation of incidents and near accidents. Human factors research is becoming involved in this process, since most blunders can be attributed to human error.

Current Methodologies for Operational Standards Development

The empirical method of developing air traffic control separation criteria was adequate for early aviation, since there were few airways and relatively little traffic over any particular area. The probability of a midair collision was fairly low compared to other safety factors such as weather, structural failure, etc. But as newer and more precise forms of navigation became available (VORTAC and GPS), and increased traffic levels required the addition of new airways, it became necessary to codify the standards already in use. Because many of the criteria already in existence seemed to work well, most existing separation criteria have been “reverse engineered.” New standards were developed to describe the already existing separation criteria. Once defined, however, these standards could be applied to future changes to the airspace system.

With so many alternative ways of achieving the same system performance, the old paradigm of adding new subsystems and seeing what improvements it makes is no longer acceptable.

Since there are many different ways to navigate between airports within the NAS, and many different ways to effect safe separation of aircraft, it was necessary to develop one accuracy standard that all navigation systems in use could meet. These standards typically define the sum of the maximum probable two-dimensional (lateral and longitudinal) errors in aircraft positioning. The third dimensional variable considered in ATC is altitude, and since altitude is measured through self-contained barometric instrumentation, these standards are developed differently and do not apply to AHS.

The following subsections discuss the current methods for establishing operational standards—focusing on the dependence of CNS technologies on operations. *An important parallel for AHS is to understand the interdependence that all three of these technologies have in determining the operational standards.*

Navigation

In aviation, vehicles are rated for operation in different classes of airspace where navigational accuracy criteria vary. This may be a practical option for AHS.

There are two defined classes of airspace within which navigational accuracy criteria are specified: class I and class II navigational airspace. Class I navigation occurs within airspace served entirely by internationally approved navigation facilities (NDB, VORTAC, and eventually GPS). This airspace typically includes that overlying most of North and South America, Europe, Japan and other industrialized nations. Class II airspace is any airspace not categorized as class I and includes any airspace outside the operational service volumes of internationally approved navigation aids. This airspace typically exists over the oceans, the two poles, and over third-world countries. The future implementation of GPS worldwide will not convert all class I airspace into class II as GPS coverage will remain incomplete in some areas. The United States is entirely class I airspace, requiring greater navigational accuracy, while the North Atlantic track system lies entirely within class II airspace.

Navigation performance factors into risk probability and separation standards.

Collision Probability Factors—For the purpose of traffic separation, aircraft operating within the National Airspace System can be visualized as traveling within a moving three-dimensional box of airspace. The dimensions of this box vary based on a number of factors, including the accuracy of the navigation system in use, distance from the navigation aid, and the aircraft's speed. It is assumed by the FAA in the collision risk equation that there is a 95% probability the aircraft will remain within this three-dimensional box during normal navigation maneuvers. It is also assumed that major navigational blunders will most likely take the aircraft out of its assigned airspace box. Separation between two aircraft is reasonably assured as long as no portion of any box overlaps the airspace assigned to another. This concept is visually demonstrated in Figure 23.

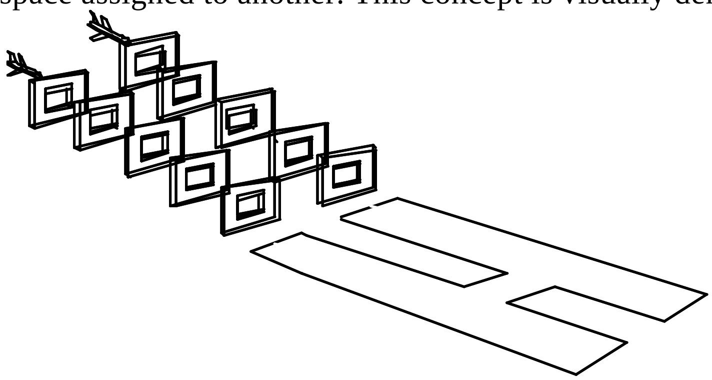


Figure 23. Concept Visualization of Collision Risk Boxes

Factored into the collision risk equation is the probability of collision if one aircraft temporarily deviates from its position box. This collision probability is based upon the density of air traffic and the exposure time for each aircraft. For example, two aircraft, each on parallel one-way airways, have a low exposure level to one another. They are only exposed to possible conflict as they pass each other in opposite directions. Two aircraft flying in the same direction on the same airway, one behind another, will have a higher total exposure time, necessitating an increased separation interval. Risks not calculated into the equation are unplanned flight path deviations due to aircraft emergencies, navigation, communication and/or surveillance equipment malfunctions, and air traffic control operational errors.

Surveillance

The vehicle/pilot is primarily responsible for navigation. ATC is primarily responsible for surveillance. Both have responsibility for communication.

In many situations, ATC does not have an independent means such as radar to monitor air traffic and must depend entirely on information relayed from an aircraft to determine its actual geographic position and altitude. In this situation, a flight crew's precision in navigating and communicating the aircraft's position is critical to ATC's ability to provide safe separation. Even when ATC has an independent means such as radar to verify the aircraft's position, precise navigation and position reports, when required, are still the primary means of providing safe separation. In most situations, ATC does not have the capability nor the responsibility for navigating the aircraft. ATC relies on precise navigation by the flight crew. *Therefore, safety depends primarily on the operator's ability to achieve and maintain certain levels of navigational performance. ATC radar is used to monitor navigational performance, detect navigational blunders, and expedite traffic flow.*

System throughput is proportional to the level of surveillance services available. If surveillance coverage decreases, the number of vehicles that can be safely handled also decreases.

Air traffic control surveillance of aircraft is factored into the establishment of separation standards. If surveillance methods are utilized that make it likely that the ATC system will be able to detect and correct pilot deviations and blunders quickly, the separation standard may be reduced to 3 miles in normal conditions and as little as 1/2 mile in special situations. It is assumed when making this calculation that up to 25 seconds may be required for the controller to detect, evaluate, correct, and communicate corrective action to the aircraft. If little or no surveillance can be provided, the separation standard must then be increased, since ATC oversight is not available to correct aircraft blunders. The FAA, therefore, only provides radar surveillance in accordance with priorities developed using a separate risk assessment formula.

This risk assessment formula is conducted in two phases. Phase I applies generalized cost/benefit-safety formulas to determine whether a formalized airspace study should be conducted. Phase II calculates relative economic benefits through the calculation of theoretical aircraft delay reductions, assuming the installation of radar. The potential reduction of midair collisions based upon the installation of surveillance equipment (radar) is then calculated. Each of these equations is weighted toward commercial and military operations.

If Phase I indicates a cost/benefit ratio in excess of 1.0, a detailed airspace study is conducted to determine whether the radar surveillance needs can be met in any other manner. If not, the FAA places the airport on a list for potential radar installation.

The accuracy of ATC surveillance is also a factor in the separation equation. If the surveillance equipment is fairly inaccurate, either due to equipment deficiencies or aircraft distance from the radar, and/or aircraft position information is time delayed, separation criteria must be increased. Increased positional accuracy and/or frequency of positional update may reduce the required separation.

Communications

Verbal communication has been the primary mode of communication between the vehicle and the ground for the past 60 years.

Radio communications procedures have existed since the 1930s with very few changes. There are two general types of communications within the air traffic control system. The first, and least precise, is verbal communications utilizing either VHF, UHF, or HF radio. After World War II, the English language was accepted as the common international language. An accepted method of verbalizing specific air traffic control phrases was also agreed upon at that time. The only changes since then have been to create more channels to accommodate increased communications requirements. In general, to provide more channels, frequency spacing has been halved, resulting in changes to radio equipment TSOs that essentially require that the radio's accuracy be doubled. The frequency spacing has been cut in half at least four times in the last 50 years, requiring changes to TSOs and eventual radio replacements in the nation's fleet of aircraft about every 10–

20 years. Unfortunately, the changes to the TSOs only affect newly installed radios. Old radios may still be utilized (albeit illegally) for a considerable period of time. This requires that the FAA take into consideration possible radio frequency overlap whenever new ATC communications facilities come on line.

Digital data-links and satellite communications are not only replacing some of the old verbal traffic but also allowing for new functionality.

Primitive data transmission systems are the second type of communication in use by the FAA. These primarily include mode-C transponder transmissions from aircraft. The transponder system simply transmits a coded pulse to the ground station that identifies the aircraft and, if the aircraft is so equipped, can also transmit the aircraft's barometric altitude. Altitude transmissions are required to be within plus or minus 300 feet of the aircraft's actual altitude. The transponder system was developed from the World War II identification friend or foe (IFF) system and is governed by appropriate TSOs.

Summary of Air Traffic Control Separation Standards

ATC separation standards are a function of the following variables: assigned airspace dimensions, traffic complexity, exposure duration, communications capability, blunder detection capability, and correction. Figure 24 summarizes the factors that are considered when developing separation standards for aircraft.

Airspace Dimension is a Function of	Traffic Complexity is a Function of	Duration of Exposure is a Function of	Detection and Correction is a Function of
´ Navigation system accuracy D VORTAC ± 6Á D NDB ± 10Á D DME varies based upon altitude D ILS ± 1/2Á D GPS ± 300 ft ´ Aircraft speed D Pilot reported as airspeed ± 10 knots D Radar-derived ground speed ± 5 knots	´ Traffic density ´ Traffic complexity D Mix of aircraft; military, commercial, etc. D Aircraft with different speeds D Aircraft dynamically changing speed or configuration ´ Changes to assigned route	´ Length of flight ´ Aircraft speed	´ Surveillance accuracy D Based on type of radar D ARSR is ± 2.5 nm D ASR is ± 1.5 or ± 2.5, depending on aircraft distance from radar site ´ Communications accuracy D Depends on pilot and controller skills ´ Ability to detect blunders D Depends on controller skills ´ Ability to develop corrective action D Depends on controller skills

C940301-06

Figure 24. ATC Considerations for Developing Separation Standards

AHS, like ATM, will have extreme inter-dependence of elements within the system—complicating standards definition and development.
Figure 24 indicates the level of interconnectivity of elements within the ATM system. Separation standards are a function of multiple considerations, each of which is itself a further function of various equipment and vehicle characteristics. This coupling, or interconnectedness, will also be inherent in the AHS system. Understanding this and setting up a governing organization that can adeptly and efficiently handle such a system is paramount to the success of an AHS.

New Methodologies for Standards Development

The previous two sections summarized the historical and current methodologies for operational standards development. New technology developments in the last decade, specifically GPS and satellite communications, have resulted in a reevaluation of how standards are developed.
The explosion of new technologies has introduced the availability of several different ways of achieving the same system performance.
Three recent areas of system expansion have led to the development of a standardized methodology for the implementation of aircraft separation standards. These three events were the development of Minimum Navigation Performance Standards (MNPS) airspace over the North Atlantic, area navigation (RNAV) in the continental United States, and the introduction of the Global Positioning Satellite (GPS) system.

Oceanic operations for aircraft are similar to intercity operations for vehicles; surveillance is likely to be limited and vehicle separation standards increase correspondingly.

Minimum Navigation Performance Standard Airspace (MNPS): The North Atlantic is the most heavily traveled oceanic airspace in the world, where only limited ATC surveillance functions are available. Due to this limitation, aircraft are separated through the use of multiple parallel airways, speed restrictions, and timed departures. Communications are limited to third-party relays of high-frequency radio transmissions. Navigation is based upon inertial navigation, VLF/OMEGA, and more recently, the GPS navigation system. There is no ATC radar surveillance of traffic for most of the flight.

Rapid increases in transatlantic traffic over the last two decades have necessitated new separation and operational criteria to enable increased traffic and reduced separation. New separation standards, aircraft tracking systems, and route structures were developed as part of this expansion program.

Vehicles equipped with RNAV (a vehicle-based precision navigation system) can benefit from more flexible routing. This concept may be an option for AHS.

Area Navigation (RNAV): Area navigation permits aircraft to depart from the proven, rigid airway structure that had existed since the 1950s and permits an infinite number of off-airway direct flights. The widespread implementation of area navigation in the United States in the early 1970s required a new, methodical analysis of system operational standards. This affected previous criteria concerning airway widths, traffic complexity crossing, and converging and diverging routes.

Global Positioning Satellite (GPS) System: Within the last two years, the GPS system developed and operated by the Department of Defense has become available for civilian use. This new system offers promising improvements to navigational and communications accuracy.

System-Level Standards

It is important to note that these three developments (MNPS, RNAV, and GPS) were not instigated by the Federal Aviation Administration. In fact, in most cases, the FAA has either opposed or neglected promising improvements in the ATC system. These improvements have been imposed either by legislative action or through overwhelming pressure from system users.

Standards development often lags behind equipment development because of the FAA's reluctance to embrace new technologies.

This has caused standards development to lag behind equipment development. In most cases, because of a lack of foresight, new concepts in ATC are developed without the FAA's support; therefore, upon their eventual acceptance, they become the de facto standard. It is only after they are on the verge of becoming widely used that a systematic analysis of navigation, communication, surveillance, and air traffic control separation standards based upon that technology is developed. That process will be the basis of this section.

Newer standards for operation in specific airspace specifies requirements beyond those defined in Technical Standard Orders (TSOs). TSOs are equipment specifications, not system performance standards. Regulations regarding operations within MNPS airspace, for example, define specific system performance requirements that have been agreed upon by the international community.

New system-level standards now provide users with a choice among competing technologies and equipment—such as GPS versus radio navigation.

These are operational system standards, requiring overall system performance levels without listing specific equipment such as a TSO. Specifications for operating in MNPS airspace do not require a specific type of navigational equipment, but do require that each navigation system installed on the aircraft be TSO'd and that the entire aircraft navigation system meet certain criteria. Which navigation system is installed in any particular aircraft is left up to the aircraft operator, as long as the minimum system standard required for operation in MNPS airspace is maintained.

Overall System Accuracy—In general, the FAA attempts to develop standards that will provide navigation at a 95% confidence level. The 95% confidence level is generally accepted as an adequate standard if surveillance is being applied to airborne aircraft traveling between airports. It is generally accepted that when navigation systems are operating at that confidence level, any aircraft that exceeds standard separation criteria will be quickly detected and corrective actions will be communicated to the pilot. In many cases, the aircraft may be in flight conditions that will permit visual observation and collision avoidance.

Vehicles are allowed to perform certain procedures based upon the rated performance of their on-board equipment.

During the approach phase of flight, however, when aircraft may not be able to visually maneuver and the aircraft is descending closer to the ground and/or obstacles, the principal risk to the aircraft is no longer collision with another aircraft but with immovable, fixed objects such as terrain, man-made structures, etc. Since these obstructions are fixed collision risks, with 100% exposure to the aircraft, the FAA mandates a higher confidence level for the navigation system. Various navigation systems are available for instrument approaches, each with varying levels of accuracy. Based upon the accuracy of the navigation system involved, between 97.5% and 99% confidence levels are required for the procedure to be approved.

APPLICATIONS TO AUTOMATED HIGHWAY SYSTEMS

This chapter concludes by summarizing, in list format, the AHS relevant, top-level criteria and assumptions that go into the development of ATM standards.

Most of the system design paradigms, parameters, probability calculations, traffic management programs, and general assumptions involved in the National Airspace System are directly applicable to automated highway systems. The primary differences between the two center around resolution and timing.

The air traffic control system provides separation that varies between 1/2 and 60 miles between aircraft. Highway separation will be measured in inches and feet. Traffic density at even the nation's busiest airports is just a fraction of that found on a typical interstate highway. Navigation and control systems for highways will need to be far more accurate than those used in air traffic control.

The surveillance, communications, and navigation functions will also need to be more precise for AHS. Air traffic control radar updates aircraft position every 10 to 20 seconds. As previously stated, navigation blunders in ATM may take up to 25 seconds to detect and correct. This is obviously an excessive interval for automobiles operating within meters of each other.

Although there are differences in required precision and frequency of events between ATM and AHS, many of the basic ATM system-level assumptions apply directly to AHS.

Other than these problems, the basic assumptions of air traffic control can be applied to automated highway systems. These basic assumptions, adapted for automated highway use, are summarized below. The criteria are organized into the seven categories shown in Figure 25.

- Prototype Evaluation
- Initial System Design
- User Input
- Standardization
- System Operation
- Service
- Evaluation

Figure 25. Categories for Criteria Related to Standards Development

Prototype Evaluation

Any prototype system that is developed ought to be evaluated utilizing the following criteria adapted for automated highway systems:

- The system ought to be suitable for use in all vehicle types that may require the service without limiting the performance characteristics or utility of those vehicle types; e.g., maneuverability and fuel economy.
- The system ought to be safe, reliable, and available; and appropriate elements ought to be capable of providing service over all desired roadways, regardless of time, weather, terrain, and propagation anomalies.
- The integrity of the system, including the presentation of information in the vehicle, shall be as near 100% as is achievable and, to the extent feasible, should provide warnings in the event of failure, malfunction, or interruption.
- The system ought to have a capability of recovering from a temporary malfunction (e.g., loss of signal) in such a manner that the vehicle's system can recover without the need for complete resetting (*fail soft).*
- The system ought to automatically present to the operator adequate warning in case of malfunctioning of either the vehicle-based or source element of the system. It ought to ensure ready identification of erroneous information that may result from a malfunctioning of the whole system and, if possible, from an incorrect setting.
- The system ought to provide in itself maximum practicable protection against the possibility of input blunder, incorrect setting, or misinterpretation of output data.
- The system ought to provide adequate means for the operator to check the accuracy of vehicle-based equipment.
- The system ought to provide information indications that automatically and radically change the character of its indication in case a divergence from accuracy occurs outside safe tolerance.
- The system signal source element ought to provide timely and positive indication of malfunction.
- The navigational information provided by the system ought to be free from unresolved ambiguities of operational significance.

_ Any source-referenced element of the total system should be capable of providing operationally acceptable navigational information simultaneously and instantaneously to all vehicles that require it within the area of coverage.

_ In conjunction with other instrumentation, the system ought to in all circumstances provide information to the operator and vehicle systems for performance of the following functions:

- Continuous tracking guidance
- Continuous determination of distance along track
- Continuous determination of position of vehicles
- Position reporting

– Manual or automatic operation

_ The information provided by the system ought to permit the design of indicators and controls that can be directly interpreted or operated by the operator.

_ The system ought to be capable of being integrated into the overall traffic control system.

_ The system ought to have sufficient flexibility to permit changes to be made to the system of routes without imposing unreasonable inconvenience or cost to the providers and the users of the system.

_ The system ought to be capable of providing the information necessary to permit maximum utilization of highways.

_ The system ought to be cost-effective to both the Government and the users.

_ The system ought to employ equipment to minimize susceptibility to interference from adjacent radio-electronic equipment and shall not cause objectionable interference to any associated or adjacent radio-electronic equipment installations in vehicles or on the ground.

_ The system ought to be free from signal fades or other propagation anomalies within the operating area.

_ The system ought to be comprised of the minimum number of elements that are simple enough to meet, economically and practically, the most elementary requirements yet be capable of meeting, by the addition of suitable elements, the most complex requirements.

_ The system ought to be capable of furnishing reduced service to vehicles with limited or partially inoperative equipment.

_ The system ought to be able to provide indication of a failure or out-of-tolerance condition of the system.

Initial System Design

_ The main components of the standard setting process ought to include:

- An initial determination of a target level of safety.
- The development of methods for deriving separation values based on technology-independent needs.
- All system development should take into consideration future systems enhancements.

–After separation criteria have been established, criteria for the application of those separation values ought to be developed.

- _ An acceptable accident rate ought to be determined and accepted by system designers and users.
- _ The acceptable accident rate ought to take into account
  - – The sum of the normal risks.
  - – Unplanned vehicle deviations such as emergency deviations and system failures.
- _ When making safety calculations, if the value of a parameter is not known, an assigned limit argument ought to be used rather than an arbitrary judgment.
- _ Separation standards ought to provide sufficient room for vehicles to exhibit normal navigational fluctuations about their intended position.
- _ The vehicle separation system should take into account all possible directions from which conflicting traffic may approach.
- _ To optimize the system, the goal ought to be to:
  - – Provide higher vehicle concentration within a given area than is possible without automated systems.
  - – Cause minimum deviations from optimum travel routes.
  - – The system should cause minimal delays.

User Input

Once these developmental criteria have been defined, appropriate user groups ought to be consulted to further refine the concept. Some of the factors that ought to be considered include:

- _ Vehicle speed, size, and maneuverability.
- _ Regulated and unregulated traffic flows.
- _ Driver skill levels and workload.
- _ Processing and display requirements for navigational information.
- _ Environmental constraints.
- _ Operational constraints inherent to the system.
- _ Economic benefits.
- _ Vehicle performance variables such as fuel consumption, operating costs, and cargo value.
- _ Cost/performance tradeoffs of equipment.

Standardization

_ A necessary degree of standardization and interoperability ought to be recognized and accommodated

_ Navigation services and systems ought to be technically and politically acceptable to diverse groups, including states and localities, private and commercial vehicle operators.

System Operation

_ Systems ought to be responsive and flexible to changing operational and technological environments.

_ Modification and transition of systems should occur in an orderly manner to accommodate technical improvements.
_ Systems ought to be provided to a variety of user classes with the minimum number of subsystems.
_ Services ought to be provided in all relevant operating areas.
_ Research and introduction of new systems and concepts ought to be considered, particularly where requirements or cost savings are not met.

Service

_ Services sufficient to allow safe transportation ought to be provided.
_ To the extent possible and consistent with cost-effectiveness, services that benefit the economy ought to be provided.

System Evaluation

_ Evaluation of the acceptable level of safety risks to the Government, user, and general public as a function of the service provided.
_ Evaluation of the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the service desired measured against the benefits obtained.
_ Evaluation of the total cost impact of any government decision on system users.

CHAPTER 6: NEW AUTOMATION TOOLS IN ATM

Traffic Management is a secondary role for ATC but is growing in importance.
As previously described, the air traffic control system is primarily concerned with surveillance, not navigation. This results in an aviation system that, although safe, may not operate efficiently. The goal of the various traffic management system (TMS) projects within the FAA is to increase overall system efficiency without reducing safety standards.

Smoothing peaks and valleys is a main goal of traffic flow management.
Most of the efforts toward increasing ATC system efficiency center around smoothing out peaks and valleys in traffic flows. As operational experience has been gained in the ATC system, theoretical maximum traffic values for various components of the system have been calculated. These components include airports, final approach routes, specific intersections, and air traffic control sectors. Virtually all of the traffic management initiatives of the FAA attempt to dynamically match traffic demand with the theoretical maximum traffic values for these components.

The following programs have been initiated by the FAA in an attempt to efficiently *manage* the increasing air traffic. These programs highlight the “areas of weakness” in today’s ATM system and as such serve as warnings to AHS developers. Figure 26 shows where these programs fit into the ATM system, and the corresponding AHS system elements are shown for reference.

Figure 26. Current FAA Automation Programs

Departure Delay Program

Lane capacity will be dynamic—varying with weather, noise requirements, traffic patterns, construction, etc.

One of the first FAA programs involved an attempt to match actual airport demand with a calculated airport acceptance rate (AAR). AAR is a dynamic variable that considers weather conditions, available runways, noise abatement routes, and traffic flow patterns to determine the maximum number of aircraft that can land at an airport during any given time period.

Higher efficiency is achieved the *sooner* actions can be taken. The concept is similar to rerouting commuters as they leave work rather than holding them at ramp meters.

The Air Traffic Control System Command Center (ATCSCC) located in Washington, D.C., continually calculates airport acceptance rates for the major airports in the United States and determines whether predicted airport demand will exceed that value for any given time period. If it appears likely, the ATCSCC delays aircraft departures in an attempt to match eventual arrivals to the airport's acceptance rate. For example, if snow in Minneapolis shuts down one runway, ATCSCC may hold Minneapolis-bound planes on the ground in Boston and Detroit. There is a direct correlation between operating efficiency and the timeliness of information: the sooner information is available, the more efficiently (or near optimal) the system can perform.

This program is not highly automated as the airport acceptance rate can change dramatically based upon unforeseen and unpredictable variables, such as rapidly changing local weather conditions, runway closures, etc. The FAA will admit that it is more of an art than a science—computer-assisted art, but art nonetheless.

Aircraft Metering Program

The departure delay program is unable to make near-term corrections to the system since it can only affect aircraft that have not yet departed. In any case, imposed delays only grossly affect the actual arrival times of aircraft. Unknown variables such as winds aloft, aircraft loading, and pilot selection of airspeed will likely change the ultimate arrival time of the aircraft at the airport of intended landing.

AHS parallel—the aircraft metering tool is similar to an automation tool for AHS traffic management controllers that would aid in determining access rates to AHS lanes.

The aircraft metering program is a computer program that attempts to fine tune this process. As aircraft proceed toward their destination, the air traffic control surveillance system begins to calculate actual arrival times at the airport. If it becomes apparent that the airport acceptance rate will be exceeded, the metering program calculates appropriate delays for each inbound aircraft. This information is calculated by the Traffic Management Unit (TMU) located in each air route traffic control center. The TMU controllers verify the data, and electronically pass it along to the controller actually working the aircraft.

Traffic Management Units try to minimize the shared *sum of delays* experienced by all aircraft in their Center.

The aircraft metering program calculates time and distance from each aircraft to the airport and issues the exact time that each aircraft should cross a predetermined fix. It is left up to the controller to determine the means of delaying the aircraft. Route changes may be employed, as may speed restrictions. The overall goal of the metering program is to ensure that aircraft arrive at the airport in a proper sequence so that none have to enter a holding pattern for any length of time.

En-route Sector Loading Program

AHS parallel—ELOD is similar to an AHS Link management tool where vehicles are rerouted based on real-time “load” conditions such as accidents.

Each Air Route Traffic Control Center is divided into multiple sectors. From one to three ATC controllers are assigned to each sector. The En-route Sector Loading Program (ELOD) is a dynamic computer program operated by the TMU within each air traffic control center. ELOD constantly compares the saturation of individual control sectors and notifies the TMU if any sector is predicted to overload in the near term. Whenever a future overload is predicted, the controllers in the TMU empirically determine the nature and cause of the overload (e.g., weather fronts), determine whether it is a transient condition or an immediate problem, and manually initiate aircraft rerouting if necessary.

Center/TRACON Automation System

The problem inherent with each of the above-mentioned programs is that the only action to be accomplished is aircraft delay or rerouting, which is hardly conducive to an efficient ATC system. Once the aircraft are within 30 miles of the destination airport, and properly sequenced by the previously mentioned traffic management programs, it becomes the air traffic controller’s responsibility to assign route and airspeed changes to merge inbound traffic flows and ensure that the aircraft arrive at the runway properly sequenced. Due to variables such as weather, aircraft performance, pilot preferences, traffic density and complexity, this task is inherently very difficult to model. Human controllers find this task difficult to perform, and most FAA initiatives to assist the controller have not had much success.

Equipment can be introduced much quicker if it is first used to *advise* the driver or controller rather actually performing safety-critical functions.

In recent years, a NASA-sponsored project, the Center/TRACON Automation System (CTAS), has been conducted to provide the controller with sequencing assistance. CTAS attempts to provide the controller with the tools that permit efficient spacing of aircraft as they line up for their final approach to the runway. CTAS attempts to calculate all the variables involved and advise the controller of the most efficient route for each aircraft to fly.

A modification of this system has been experimentally installed at Boston's Logan airport. The Boston airport has converging approaches that require specific and difficult aircraft spacing for efficient airport utilization. The prototype system at Boston creates phantom targets on the controller's display. If the controller vectors inbound aircraft to precisely follow these "targets," proper spacing between two runways is achieved. This system relieves the controller of the grueling mental task of trying to calculate the optimal routes for each aircraft. The computer system accomplishes that. It is left up to the controller to guide each inbound aircraft using the computer-suggested route and sequence.

Automation does not always improve efficiency. Automation "hardwires" rules and regulation into its logic, whereas skilled human controllers can *bend* the rules if the circumstances demand.

A very interesting side effect of the CTAS automation tool that has recently come to light is that in some instances during peak traffic periods, the tool may actually be reducing the system capacity. The automation tool has "hardwired" in the FAA separation standards for all aircraft types. During extreme peak periods, good controllers were known to "push" those standards and actually handle more aircraft that the CTAS tool can. Although safety levels may have been compromised during these periods of excess capacity handling, perhaps occasionally the circumstances called for it. This unique twit on expected performance is worthy of further analysis.

CHAPTER 7: SUMMARY OF LESSONS LEARNED

This chapter consolidates, in list format, all the side-bar comments from chapters 1 through 6. In most cases these are the lessons learned and/or recommendation. For quick reference page numbers and a reference topic are provided.

Reference Topic	***Page Num.***	***Side-bar Comment (Lessons Learned or Recommendation)***
Establishing the Comparison	1	The radio-defined skyways that layer our national airspace resemble in many ways an interstate highway system. Air Traffic *Management* (ATM) is the correct comparison for AHS.
CNS Technologies	2	Improvement in communication, navigation, and surveillance technology and the intelligent use of automation is at the heart of ATM (and AHS).
CNS Technologies *Traffic Management*	4	ATM and AHS are built upon similar communication, navigation, and surveillance (CNS) technologies. Increasing system efficiency through automated Traffic *Management* is a relatively new role for the FAA.
System Objectives	6	Increasing capacity while maintaining (or improving) safety is the foremost objective of both AHS and ATM.
System Functionality	8	AHS and ATM share many operational functions; everything from vehicle check-in through to transition and back to manual control and vehicle checkouts.
System Architecture	10	The layered architecture being proposed for AHS is consistent with the current ATM system architecture.
CNS Technologies	11	AHS and ATM are built upon the same core technologies: communication, navigation, and surveillance.
CNS Technologies	13	Even though the core CNS technologies are the same, the AHS system is in many ways a more challenging problem.
Establishing the Comparison	14	Similar objectives, similar operations, similar functional requirements, and similar technologies result in similar issues, risks, and lessons learned.
Lessons Learned Analysis	15	Trends often indicate changes in fundamental philosophies. Understanding the reasons for these changes are the Lessons

Centralized Control	15	Learned that we are seeking. ATC is a centralized system—all communication goes through ATC. As capacity demands grow, this centralization has become a bottleneck.
Centralized Control	15	The vehicle-based TCAS system has introduced an element of decentralization.
Vehicle Autonomy	16	The trend in aviation is toward smart vehicles. We recommend AHS follow suit. The FAA has been unable to keep pace with equipment manufacturers. Highly capable aircraft are significantly limited by aging ground-based equipment.
Traffic Management	17	Cost/Benefit analyses must take into account the extreme inter-connectivity of such a complex system. Increasing traffic demands necessitated the move from tactical traffic control to strategic traffic management.
Requirements	18	Subsystem performance requirements that are dependent on a specific technology will artificially inhibit the introduction of new technology and will *hinder the evolution* of the system.
Requirements	19	AHS should avoid technology-derived standards by doing thorough system analysis and determining the actual *system* requirements.
Role of the Driver	20	The issue of *who* (or what) has ultimate responsibility for the safe operation of the vehicle must be addressed before further development. In ATM the pilot has ultimate responsibility. This has significant implications for liability litigation.
Role of the Driver	21	Every effort should be made to assist the driver in detecting all errors, *including his own*
Reliability	22	AHS should be built upon multiple levels of *independent* supervision: conceptually, theoretically, and functionally independent. Ultra-reliability can only be assured with reasonable certainty by means of overlapping layers of supervisory failure-compensating systems. AHS should adopt the FAA safety-criticality classification process but should re-derive the reliability numbers that define those

		classifications. For deriving reliability requirements, consider using the Risk Tree Methodology currently being developed by the FAA.
Reliability	23	A Target Level of Safety has to established for AHS before significant system design can proceed.
Reliability	23	Attempts to achieve substantial system-level reliability by requiring ultra-reliable subsystems (gold-plated electronics) are misguided, impractical, and *costly*.
Reliability *Reliability*	24	Ultra-reliability of safety-critical software cannot be *verified*. Many software errors can be traced back to the *specification* . . . as undocumented *requirements*. Overall system reliability must be achieved through *independence*, not through unverifiable subsystem reliability requirements.
Reliability	26	*There comes a point where decreasing the error tails of equipment may actually DECREASE system safety*.
AHS Operations	28	*Lesson Learned*—The AHS will be faced with vehicles of varying performance. Quotas for permitted usage by varying vehicle types may need to be established. *Mixed-vehicle-type traffic limits capacity*.
AHS Operations	29	AHS administrators must understand the balance between *equitability* and *capacity*.
AHS Operations	30	*Lessons Learned*—In the implementation of an AHS, at some point the issue of a failure to merge into the automated traffic stream must be addressed. The key issue is how the driver will identify the lack of a successful merge, and the corresponding driving response. In AHS, the Go/No-Go decision point for safely merging into automated traffic may be dependent on vehicle type. After that “point,” a vehicle is committed to executing a merger. *AHS parallel*—Go/No-Go decision criteria may vary from one location to another within AHS.
Communications	31	*Lessons Learned*—In aviation, there are no examples of vehicle-to-vehicle or vehicle-to-ground communications that are considered *safety-critical*. If AHS developers choose a system design with safety-critical

		communications, significant technology and standards development will be required.
Communications	32	There are examples of *mission-critical* communication systems in the space industry that we may be able to apply to AHS.
Role of the Driver	33	*Lesson Learned*—There are a number of ways to distribute system functionality between the roadside and the vehicle, but final authority for safe operation should rest with the user.
Standardization	34	*Lessons Learned*—If it is intended that the AHS not have unique training requirements for usage, then it will be necessary to minimize the number and nature of any site-specific Standard Operating Procedures (SOP) across AHS implementations nationwide.
Vehicle Compliance	35	*Lessons Learned*—The most important point to note is that although the vehicle manufacturer must be involved in the development of an Minimum Equipment List (MEL), it is up to the operator, not the vehicle manufacturer, to comply with the minimum equipment set. This has significant implications with regard to aviation product liability litigation. There are a number of means by which compliance with a functioning minimum equipment suite could be communicated to the AHS, such as standardized built-in-test (BIT), which transmits results to the roadway, or a discrete “check-in” process could be mandated so that all vehicles entering the AHS are given a diagnostic inspection before being admitted.
Fail-Operational Requirements	36	*Lessons Learned*—If the AHS is designed to minimize the need for driver training, then it will be mandatory for the system to be Fail Operational to the extent it can remove a vehicle safely from the AHS and return control to the driver when the driver indicates a readiness to resume manual control.
Performance Monitoring	37	*Lessons Learned*—If performance monitoring were part of the roadway infrastructure, the cost of instrumenting individual vehicles with specialized AHS equipment would be reduced by the cost of the BIT equipment (although redundancy, such as mentioned, could be achieved through a combination of built-in-test and roadway-based performance checking).
Driver Aids	38	*Lessons Learned*—Driver aids in terms of enhanced or synthetic vision systems to help the driver see and avoid obstacles under periods of low visibility will mitigate the effect of low visibility on

		the driver's ability to resume control and exit the AHS.
Standardization	39	*Lessons Learned*—All attempts at common "look and feel" between current and future systems should be a design goal.
Automation Philosophies	40	*Lessons Learned*—Obvious control and display implementations are needed so that the current state of automated control is obvious as well as complex routing information. It will be important to keep in mind the requirement for roadside intervention for a simple-to-use driver interface for the AHS.
Communication	41	*Lessons Learned*—The integration of a vehicle-to-vehicle communication function for collision avoidance must be implemented in such a manner as to be compatible with the system-wide maneuvering of vehicles. The collision avoidance maneuver must specifically be coordinated with any centralized control function for an AHS.
Operational Standards *Standards* *Operational Issues*	44	*Lessons Learned*—Either national standards or mandated agreements between adjacent AHS control centers are required for "seamless" operations. Standards development, not technology development, is today's main hurdle in improving the ATM system. *Lessons Learned*—Adjacent AHS control centers must be honest with one another in terms of allowing incoming traffic, up to capacity handling.
Communications *Standardization*	45	Key to the future of ATM (and AHS) will be reliable, and honest, two-way communication(11) *Lessons Learned*—The driver interface for AHS control should be standardized so that the driver would see the same conventions for the AHS interface in the vehicle in terms of location-color-text messages.
Role of the Driver *Autonomous Vehicle Control* *Autonomous Vehicle Control*	47	*Lessons Learned*—Accounting for the role of the user (driver) in regaining control for AHS failure, system status should be presented in an unambiguous manner. The Autoland system operates in a manner identical to the AHS; that is, the vehicle maintains velocity and guidance without any input from the user. *Lessons Learned*—The problem with Autoland is the very real possibility that after the successful landing, the pilot may *not* be

		able to see to taxi the aircraft off the runway! The alternative technology of enhanced or synthetic vision may be perfectly suited to providing low-visibility navigation capability to avoid bottlenecks at the egress of the AHS.
AHS Operations	48	To avoid inhibiting AHS system performance to the "least common denominator," we recommend type-rating vehicle based on the on-board equipment. In this way, for example, commercial vehicles could continue to use AHS in poor weather conditions if the vehicles were so rated, while personal vehicle operators without the proper rating would be prohibited.
AHS Operations	49	*Lessons Learned*—Fuel Efficiency can in fact be a goal for lane selection in a multilane AHS. If there are multiple lanes, the left-most lane can be restricted in terms of the number of entries or exits per unit of distance to reduce the number of speed fluctuations.
Equipment Standards	51	Historically, performance and accuracy standards were backwards engineered from the capability of available technology.
Equipment Standards *Role of the Government* *Equipment Standards*	52	The trend today is toward defining performance standards that are independent of specific technologies. The FAA has the unique role of being the regulatory agency for the very equipment they own and operate. Many claim it is too difficult to maintain the necessary objectivity. Technical Standard Orders (TSOs) ensure that manufacturer equipment is compatible with the FAA-owned and -operated ground-based equipment.
Equipment Standards	53	General standards are established and used to evaluate alternative system configurations.
Equipment Development	54	The lack of end-user involvement early on in development programs has been cited as the reason for several unsuccessful FAA programs. For most users, cost is generally the driving consideration. The price users are willing to pay for equipment is influenced by the activity of the user: air carrier, air taxi, general aviation, helicopters, etc.
  Equipment Development	55	Multiple contractors develop concepts independently. General system criteria are defined in the Federal Radionavigation Plan prepared jointly by the DOT and DOD.

		Replace the words *pilot* with *driver* and *aircraft* with *vehicle*, for example, and all of the criteria listed here apply directly to AHS-type equipment.
Equipment Development	57	The FAA's hierarchy of selection criteria normally gives precedence to system safety, reliability, and then cost.
Operational Standards	58	Historically, operational standards have been developed empirically through trial and error. The trend today is toward a more theoretical analysis of the needs of the users and requirements of the system.
Operational Standards	59	Operational standards, as with equipment standards, have been developed empirically. Analytical methodologies are often inadequate for developing operational standards due to our inherent inability to predict and model operator (pilot and driver) blunders. Analyzing operational deviations using statistical methods fail due to the one-of-a-kind nature of most incidents.
Operational Standards	60	Data reporting, collection, and analysis of *incidents* is crucial to the continued development and refinement of operational standards. An exemplary system is the anonymous Accident Reporting System (ARS) used by the FAA. With so many alternative ways of achieving the same system performance, the old paradigm of adding new subsystems and seeing what improvements it makes is no longer acceptable.
   Operational Standards	61	In aviation, vehicles are rated for operation in different classes of airspace where navigational accuracy criteria vary. This may be a practical option for AHS. Navigation performance factors into risk probability and separation standards.
Importance of Independence *CNS Technologies*	62	The vehicle/pilot is primarily responsible for navigation. ATC is primarily responsible for surveillance. Both have responsibility for communication. System throughput is proportional to the level of surveillance services available. If surveillance coverage decreases, the number of vehicles that can be safely handled also decreases.
Communication	63	In aviation, verbal communication has been the primary mode of communication between the vehicle and the ground for the past

Communication		60 years. Digital data-links and satellite communications are not only replacing some of the old verbal traffic but also allowing for new functionality.
Standards Development	64	AHS, like ATM, will have extreme inter-dependence of elements within the system—complicating standards definition and development. The explosion of new technologies has introduced the availability of several different ways of achieving the same system performance.
Standards Development	65	Oceanic operations for aircraft are similar to intercity operations for vehicles; surveillance is likely to be limited and vehicle separation standards increase correspondingly. Vehicles equipped with RNAV (a vehicle-based precision navigation system) can benefit from more flexible routing. This concept may be an option for AHS. Standards development often lags behind equipment development because of the FAA's reluctance to embrace new technologies.
Operational Standards	66	New system-level standards now provide users with a choice among competing technologies and equipment—such as GPS versus radio navigation. Vehicles are allowed to perform certain procedures based upon the rated performance of their on-board equipment.
	67	Although there are differences in required precision and frequency of events between ATM and AHS, many of the basic ATM system-level assumptions apply directly to AHS.
Traffic Management	72	Traffic Management is a secondary role for ATC but is growing in importance. Smoothing peaks and valleys is a main goal of traffic flow management.
Traffic Management	73	Lane capacity will be dynamic—varying with weather, noise requirements, traffic patterns, construction, etc. Higher efficiency is achieved the *sooner* actions can be taken. The concept is similar to rerouting commuters as they leave work rather than holding them at ramp meters.

		AHS parallel—the aircraft metering tool is similar to an automation tool for AHS traffic management controllers that would aid in determining access rates to AHS lanes. Traffic Management Units try to minimize the shared *sum of delays* experienced by all aircraft in their Center.
Traffic Management	74	AHS parallel—ELOD is similar to an AHS Link management tool where vehicles are rerouted based on real-time "load" conditions such as accidents. Equipment can be introduced much quicker if it is first used to *advise* the driver or controller rather actually performing safety-critical functions.
Role of Automation	75	Automation does not always improve efficiency. Automation "hardwires" rules and regulation into its logic, whereas skilled human controllers can *bend* the rules if the circumstances demand.

APPENDIX A: Elemental Functions

Under the Precursor Systems Analysis for AHS Health Management contract, Honeywell performed a detailed functional decomposition of an Automated Highway System.[8] These functions were categorized hierarchically according to their position in the architectural model shown below in Figure 27.

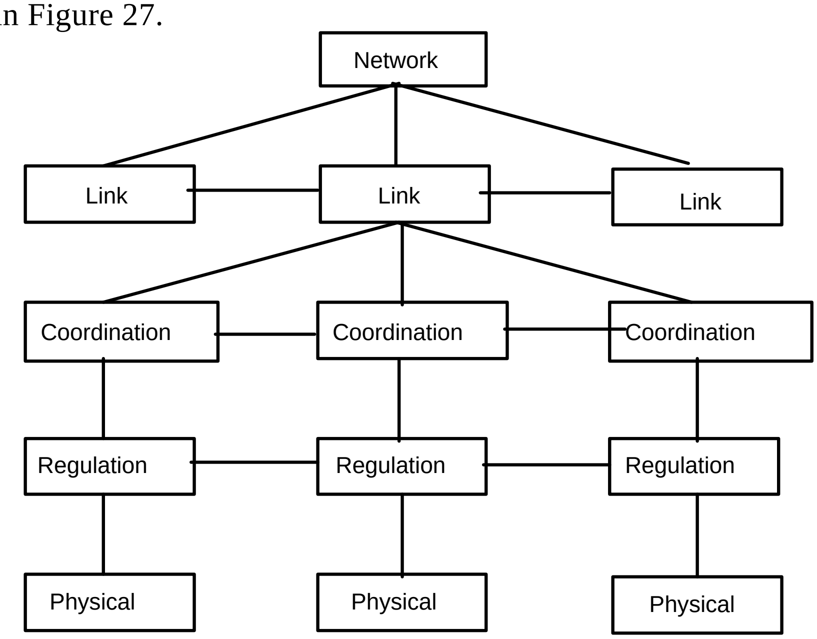


Figure 27. Proposed AHS Architecture Model

We used the results of this functional decomposition to compare AHS to Air Traffic Management function by function. The purpose of this exercise was to be as comprehensive as possible in our comparison of the two systems.

The results are documented in matrix format on the following pages. The entire functional decomposition is included here for completeness however, for the scope of this study the comparison to ATM was only performed for the top level functions. For each of these AHS functional element, the matrix gives:

- AHS Functional Description
- Comparable Air Traffic Management Function
- Description of the Comparison
- Lessons Learned

Fun-ction	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
N1	**Monitor traffic condition and predict congestion**	The network layer manages network traffic data and predicts when and where congestion will occur based on real-time traffic information.	FAA Traffic Flow Management Unit (Washington, D.C.)	The National Flow Management Unit is the central clearinghouse for route assignment and prediction of congestion based upon ambient conditions.	This function is accomplished because the National Air Space (NAS) is administered and controlled by a single federal agency (FAA). This function will likely be distributed at regional levels for AHS.
N2	**Recommend route**	Upon receiving the location and the destination of a vehicle, the network layer may recommend the shortest/fastest route. Route recommendation may be provided at the beginning of a trip or anytime during the trip.	FAA Flight Progress Strip/Air Traffic Controller	The National Flow Unit fulfills routing requests as slots become available. Aircraft are held on the ground (fuel savings) if routing or destination congestion is likely. Regional controllers are allowed to amend clearance.	There is a cascade of unpredictable complications “downstream” of an amended clearance. The FAA and Mitre are working on a new system (AERA II and III) that will predict future conflicts. This system will cross controller jurisdictions.
N3/N4	**Communicate with link layer**	The network layer receives information regarding regional traffic condition and route selection request from the link layer.	Bidirectional message traffic to/from FAA Host computers. (such as traffic hand-off between adjacent sectors).	Among the FAA ATC computers there is a free exchange of data.	The communication protocols between computers must be accounted for in the design and implementation of upgraded equipment.
L1	**Assign lane**	The link layer may provide lane assignments in accordance with the selected route and traffic conditions. Lane assignments may be given before lane changing is needed and at locations such as entrance, exit, or diverging points where decisions are needed	The equivalent of a lane assignment is a “path” in three-dimensional space requires a heading (or jetway/airway) and altitude.	The equivalent “path” in three-dimensional space requires a heading (or jetway/airway) and altitude. Requested routings are normally given, unless weather or congestion mandates differently.	More sophisticated navigation equipment is enabling aircraft to fly more direct routes (fuel savings) off established airways. Although cars must follow roads, the notion of the vehicle establishing its own fuel-efficient path is germane.
L2	**Assign target speed**	The target speed is provided in accordance with the local traffic conditions.	Speed is dictated by ATC to manage and ensure compliance with separation standards.		The control of speed (assigned by ATC) when handled by automation (autothrottles) is one of the biggest workload-reducing items on the flight deck.
L3	**Set maximum group size**	When groups are used, the maximum size of group is provided based on the current traffic conditions.	No equivalent function.	No equivalent function.	No equivalent function.

	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
L4	**Set minimal separations**	The required minimal headway is provided in accordance with the weather and roadway conditions. In a system with groups, the required minimum spacing between groups is provided.	Separation standards are mandated by weather conditions, airspace usage, and aircraft mass.	Separation standards are established to prevent collisions and to protect aircraft from upsets due to wake vortices (in-trail separation during takeoff and landing).	Recent events have necessitated the development of a new separation category for the B757 (a medium-size aircraft that generates violent wake vortices). The FAA was slow to develop a new separation standard category; as a result two aircraft have crashed.
L5	**Prioritize vehicle operations**	Vehicles with special missions such as ambulances, fire engines, or high-occupancy vehicles are given priority over other vehicles.	Special handling is specified in the ATC handbook for “declared” emergencies, presidential, and other VIP or government aircraft.	The same special handling (priority) treatment currently exists.	The impact on system throughput can be affected. (There was much press given to the “haircut” aboard Air Force One that tied up the north runways at LAX for some time.)
L6	**Monitor regional traffic condition and manage incidents**	Traffic conditions are monitored. Under incident conditions, the link layer selects paths for vehicles, adjusts target speed, or instructs vehicles to change lane for diversion around incidents.	Every ATC facility has the responsibility for ensuring separation standards for the airspace under its control and for managing incidents/ accidents as they occur.	There are “planning aids” that facilitate controllers’ efforts to shunt traffic through airspace and to airports.	The aids available to controllers are a great benefit over previous, experience-driven efforts. The further into the future the aids can project, the better the planning behavior on the part of ATC.
L7	**Monitor road surface conditions and weather**	Link layer determines weather and road surface conditions based in part on vehicle traction reports.	ATC provides information regarding winds, precipitation, temperature, and barometer settings for the aircraft operating environment.		
L9/ L11	**Communicate with the network layer**	The link layer receives information regarding the traffic condition predictions and route recommendations from the network layer. The link layer may also receive information addressing the vehicle from the network layer.	Bidirectional message traffic to/from FAA host computers (such as traffic hand-off between adjacent sectors).	Among the FAA ATC computers there is a free exchange of data.	The communication protocols between computers must be accounted for in the design and implementation of upgraded equipment.
L10/ L13	**Communicate with neighboring link elements**	Receive handoff information as vehicle passes from one link to the next.	Bidirectional message traffic to/from FAA host computers (such as traffic hand-off between adjacent sectors).	Among the FAA ATC computers there is a free exchange of data.	The communication protocols between computers must be accounted for in the design and implementation of upgraded equipment.

Function	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
L8/ L12	**Communicate with coordination layer**	The link layer receives information regarding traffic condition of the subsections within the link and vehicle's destination from the coordination layer. The link layer also receives information addressing the network layer from the coordination layer.	Bidirectional message traffic to/from FAA host computers (such as traffic hand-off between adjacent sectors).	Among the FAA ATC computers there is a free exchange of data.	The communication protocols between computers must be accounted for in the design and implementation of upgraded equipment.
C1	**Perform off-vehicle inspection and monitoring**	Vehicle inspection requiring supplemental off-vehicle equipment could be performed before the vehicle enters the AHS or while the vehicle is on the AHS. These inspection and monitoring functions, which may work with on-vehicle detection/diagnostics.	Aircraft and ATC equipment are required by Federal regulation to be maintained to a specific standard by specially trained technicians.	The inspection process is fraught with errors. Technicians make mistakes, and "new" standards are developed only after problems are identified (usually after a loss of life has occurred).	The MOST IMPORTANT lesson learned is that built-in test (BIT) is the most reliable means to ensure system integrity.
C2	**Issue permission/rejection**	Based on the inspection/monittoring outcome, traffic flow, and destination parameters, the coordination layer issues permission for entering or remaining on the AHS. Should a fault(s) be detected, a rejection command will be issued.	ATC issues instructions (including denying permission for entering the system).	ATC will issue holds (both airborne and on the ground) so that congestion can be cleared up and throughput maintained.	The most efficient means of constraining system participation is to reject entrance to a system. With the superior planning tools now available, there is much less airborne holding than there used to be because aircraft are simply held on the ground.
C3	**Plan maneuver coordination**	Maneuver coordination planning determines the sequence of events for a number of vehicles performing a coordinated maneuver. Maneuvering coordination planning is performed for both normal and abnormal conditions.	Coordinated maneuvers among aircraft (treat group as a unit) do not occur. However, there are occasions (such as a runway change) that require a number of aircraft be vectored sequentially to a new path.	Movement coordination is affected and necessitated by both weather and congestion. The movement of aircraft as a "group" has not been perfected in the ATC domain.	When ATC determines a need for rerouting traffic, it is mandatory that clear, concise execution is necessary for safe operations. There are specific procedures called out in the ATC Handbook (7110.65).

Function	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
C3.1	**Plan maneuver coordination for normal conditions**	Normal maneuvers that require coordination between vehicles, such as lane-changing, merging, entering, or exiting an AHS or joining or splitting a group, are handled by the coordination layer. The coordination layer sets up coordination protocols among the	Coordinated maneuvers among aircraft (treat group as a unit) do not occur. However, there are occasions (such as a runway change) that require a number of aircraft be vectored sequentially to a new path.	Movement coordination is affected and necessitated by both weather and congestion. The movement of aircraft as a "group" has not been perfected in the ATC domain.	When ATC determines a need for rerouting traffic, it is mandatory that clear, concise execution is necessary for safe operations. There are specific procedures called out in the ATC Handbook (7110.65).
C3.2	**Plan maneuver coordination for hazardous conditions**	Under hazardous conditions, the coordination layer provides information regarding specific hazards to vehicles that are potentially affected and provides instructions for avoiding collisions.	Coordinated maneuvers among aircraft (treat group as a unit) do not occur. When an accident happens (such as a crash on landing), contingency plans are developed as procedures that are simply executed so that there is no additional risk.	Movement coordination can be required as the result of an emergency. The movement of aircraft as a "group" has not been perfected in the ATC domain.	Specific procedures reduce the uncertainty and risk associated with handling emergency (contingency) actions.
C4	**Supervise the sequences of coordinated maneuvers**	The coordination maneuvers will be monitored by the coordination layer.	Coordinated maneuvers among aircraft (treat group as a unit) do not occur. When ATC requires a group of aircraft to comply with a new routing, the controller must ensure their compliance (which is mandated by regulation).		
C5	**Obtain Vehicle ID**	Obtain identification address used to communicate with a particular vehicle.			
C6/C9	**Communicate with link layer**	The coordination layer may transfer information from the regulation layer to/from the link layer. The coordination layer may receive operating parameters such as target speed and send traffic condition information.			

Function	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
C8/ C11	**Communicate with neighboring coordination layer nodes**	Receive information on coordination maneuvers planned for neighboring coordination element's span of control.			
C7/ C10	**Communicate with regulation layer**	The coordination layer will receive vehicle status information from the regulation layer and may send maneuver commands to the regulation layer.			
R1-R3	**Provide steering, braking, and speed control command**	Braking, steering and speed commands are provided based on sensor feedback at the physical layer and possibly maneuver commands at the coordination layer.			
R4	**Manage vehicle health**	Vehicle conditions are monitored using the sensory information provided by the physical layer. Failure detection and diagnosis are performed when a system fault is discovered. Failure response actions are determined. Onboard actions are performed.			
R5	**Monitor driver health**	Ensure that the driver is prepared to undertake manual control.			
R6	**Monitor roadside health**	Roadside computer, communication, and peripheral equipment is monitored for proper functioning.			
R7	**Monitor trip progress**	Trip progress is monitored by reporting to the operator the information regarding vehicle location and traffic condition and estimated arrival time.			

Function	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
R8/ R10	**Communicate with coordination layer**	The regulation layer may receive weather and road condition information from the coordination layer as well as maneuver commands. The regulation layer will communicate status in return.			
R9/ R11	**Communicate with physical layer**	Provides control commands to the physical layer and receives sensor information.			
R12	**Detect obstacle**	Determine whether information from physical layer concerning front/rear/side detections constitutes obstacle. Includes loss of road.			
R13- R15	**Determine dynamic response of propulsion, braking, and steering systems**	Determines the acceleration capability and steering performance of the vehicle.			
R17	**Determine visibility**	The visibility will be monitored and graded.			
R18	**Convey information to operator**	Format information for display to operator.			
R21	**Provide information/ acknowledgment**	The driver will be required to provide information to the system. This includes the following:			
R22	**Perform mode selection**	Determine and initiate the appropriate mode of operation for the vehicle, including automatic, manual, and crisis operational status.			
R23	**Configure for manual operation**	Ensure that the vehicle has all functions necessary for manual operation enabled (e.g., wipers, lights, . . .).			

Function	AHS Function Name	AHS Function Description	ATM Function Equivalent	Comparison	Lesson Learned
P1	**Sensing**	Four groups of sensory information are needed. The sensory information can be obtained through direct sensing or combined sensing and signal processing. The following information may be entirely or partially needed for any specific AHS design.			
P2	**Actuation (steering, propulsion, brakes)**	Actuation is provided in two dimensions: steering and speed control. Speed control includes control of both the propulsion and the braking systems.			
P3	**Human-machine interface**	The human-machine interface enables the human operator to monitor the performance of the vehicle, to adjust performance parameters within a reasonable working range, to be aware of hazardous conditions, and to take over control tasks if necessary. It may			
P4	**Store/provide maintenance history**	Maintain record of maintenance and inspection history.			
P5/P6	**Communicate with regulation layer**	The physical layer receives control commands from the regulation layer. The physical layer provides sensory information and user requests to the regulation layer.			
P7/P8	**Communicate with adjacent vehicles**	Send/receive information to/from neighboring vehicles, such as location and potential actions.			
P9	**Perform secondary functions**	The secondary functions that exist on the vehicle such as windshield wipers and lights will be incorporated in the AHS.			

APPENDIX B: EXAMPLE OF COMMERCIAL FLIGHT FROM ORIGIN TO DESTINATION

The following is intended to provide the reader with a narrative description of the activities the flight crew of a commercial aircraft engage in for normal flight operations. The purpose of this exercise was to do an “operational” comparison of ATM and AHS. The comparable AHS operations are called out in sidebars for easy reference.

Obtain Weather Briefing

***Comparable AHS Operation*—Vehicle Check-in**

The first activity a pilot (or flight crew) will undertake in preparation for a flight is to determine the weather conditions to be encountered along the route. Certain weather conditions are so hazardous as to be a threat to safety. There is obvious danger in flight near hurricanes and cyclone activity, but thunderstorms, hail, and icing conditions pose a threat to safety as well. Additionally, the visibility along the route and at the destination in particular affect an aircraft’s ability to depart. Forecast visibility for the destination airport is vital part of a weather report or briefing. Cloud ceiling and visibility along the runway (termed runway visual range—RVR) are important due to mandated equipment (both ground-based and aircraft navigation aids) and training required for low-visibility approaches. After ascertaining the weather conditions, the pilot can then determine what sort of “rules” the flight will operate under: Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Minimum weather requirements for VFR flight are listed in Figure 28.

ALTITUDE	UNCONTROLLED AIRSPACE		CONTROLLED AIRSPACE	
	Flight Visibility	Distance from Clouds	**Flight Visibility	**Distance from Clouds
1200" or less above the surface, •••••regardless of MSL Altitude.	*1 statute mile	Clear of clouds	3 statute miles	500' below 1000' above 2000' horizontal
More than 1200' above the surface, •••••but less than 10,000" MSL.	1 statute mile	500' below 1000' above 2000' horizontal	3 statute miles	500' below 1000' above 2000' horizontal
More than 1200' above the surface •••••and at or above 10,000' MSL.	5 statute miles	1000' below 1000' above 1 statute mile •••horizontal	5 statute miles	1000' below 1000' above 1 statue mile •••horizontal

Figure 28. The Conditions Required for Flight Under Visual Flight Rules

Commercial aircraft (cargo and passenger carriers) as a rule file flight plans and conduct operations IFR.

File Flight Plan

***Comparable AHS Operation*—Route Selection**

Aircraft operating IFR are always under ‘positive control’ by ATC. Positive control means the aircraft is being monitored by ATC and following a strict flight plan with scheduled waypoint passage. This strict flight plan has a number of advantages:

- Allows for better airspace planning and usage
- Communications failures are not catastrophic because the flight plan allows ATC to predict where the aircraft is going
- Failure to cross a waypoint at an established time allows ATC to identify a potential emergency without the pilot having to report a problem (useful if aircraft has already crashed)

To file a flight plan, a pilot would normally call an FAA Flight Service Station (FSS); a weather briefing can be supplied upon request at this time as well. The pilot tells the FAA specialist the intended departure time and may request a specific routing. The FAA specialist can advise of the preferred IFR routing between the origin and destination airports. Airlines maintain control centers that file flight plans on behalf of the pilots.

The routings are along specified airways. Aircraft must be within 4 miles of the center of an airway to be considered “on course.” The airway system links radio navigation aids (usually very high frequency omnidirectional range, or VOR, transmitters). The airways serve as roads in the sky and the VOR stations are intersections. There are two classes of airways: low-altitude (below 18,000 ft) or victor airways and high-altitude (above 18,000 ft) jetways. Both altitude assignment (based upon direction of flight) and airway following are used to gain separation between aircraft. The following figures indicate the default altitudes available for both VFR and IFR flight depending upon cardinal compass heading.

CONTROLLED AND UNCONTROLLED AIRSPACE VFR ALTITUDES AND FLIGHT LEVELS			
If your magnetic course (ground track) is	More than 3000' above the surface but below 18,000' MSL fly	Above 18,000' MSL to FL 290 (except within Positive Control Area, FAR 71.193) fly	Above FL 290 (except within Positive Control Area, FAR 71.193) fly 4000' intervals
0^{o} to 179^{o}	Odd thousands, MSL, plus 500' (3500, 5500, 7500, etc.).	Odd Flight Levels plus 500' (FL 195, FL 215, FL 235, etc.).	Beginning at FL 300 (FL 300, 340, 380, etc.)
180^{o} to 359^{o}	Even thousands, MSL, plus 500' (4500, 6500, 8500, etc.).	Even Flight Levels plus 500' (FL 185, FL 205, FL 225, etc.).	Beginning at FL 320 (FL 320, 360, 400, etc.)

Figure 29. Available Altitude for VFR Flight

CONTROLLED AND UNCONTROLLED AIRSPACE IFR ALTITUDES AND FLIGHT LEVELS			
If your magnetic course (ground track) is	More than 3000' above the surface but below 18,000' MSL fly	At or Above 18,000' MSL but below FL 290 fly	Above FL 290, fly 4000' intervals
0^{o} to 179^{o}	Odd thousands, MSL, (3000, 5000, 7000, etc.).	Odd Flight Levels (FL 190, FL 210, FL 230, etc.).	Beginning at FL 290 (FL 290, 330, 370, etc.)
180^{o} to 359^{o}	Even thousands, MSL, (4000, 6000, 8000, etc.).	Even Flight Levels (FL 180, FL 200, FL 220, etc.).	Beginning at FL 310 (FL 310, 350, 390, etc.)

Figure 30. Available Altitudes for IFR Flight

The transitions between takeoff and joining an airway and then departing the airways for a landing are the most demanding phases of flight for both the flight crew and air traffic controllers. To facilitate a standard routing, specific paths are usually designated. Standard Instrument Departures (SID) and Standard Terminal Arrivals (STAR) are published three-dimensional paths that aid in the funneling of air traffic through specific corridors. In addition, Profile Descents have been developed to aid controllers in metering traffic from the en-route portion of a flight to the STAR. The Profile Descent usually includes a number of altitude and speed constraints along a path that feeds a major metropolitan airport (e.g., San Francisco, Denver, Atlanta).

Obtain Clearance (Clearance Delivery)

***Comparable AHS Operation*—Vehicle Check-in**

Approximately 30 minutes before the scheduled departure the nearest Center computer transmits a flight clearance and any other control instructions to the appropriate Control Tower. In the Control Tower flight data personnel will tear off the data, contained on a flight progress strip (FPS), and place it in a plastic caddy at the Clearance Delivery station. The pilot will make a radio call to Clearance Delivery prior to pushback (departure from the gate) to establishe what the assigned (versus requested) routing to the destination is as well as any delay information and assigned transponder code.

1	5	8	9	10	11	12
2 2A	6			13	14	15
3				16	17	18
4	7		9A			

Figure 31. Flight Progress Strip

1. *Aircraft identification.*
2. *Revision number.* Amendments to the flight plan will cause a new FPS to be printed and version numbers will be printed in this field.
2A. *FPS request originator.* Indicates the sector or position that requested the FPS, helps in routing the FPS to the appropriate control station.
3. *Type of aircraft.* Type refers to the number of aircraft in the clearance (common for the military to fly multiple aircraft under a single IFR clearance) and weight classification (e.g., "heavies" are above 300,000 lb gross weight and warrant special handling considerations). To assist controllers an equipment suffix is added to aircraft type to designate onboard equipment capabilities for transponder, altitude encoding, and navigation capabilities.
4. *Computer identification number.* Allows an alternative means to identify the aircraft for obtaining system-wide data on the aircraft.
5. *Assigned transponder code.* The code is allocated automatically according to the National Beacon Code Allocation Plan (NBCAP). Since two aircraft cannot be assigned the same transponder code while within the boundaries of the same ARTCC, the NBACP computer program attempts to assign each aircraft a transponder code that will not be the same as that assigned to another aircraft.
6. *Proposed departure time* (Universal Time Coordinates, formerly Greenwich Mean Time).
7. *Requested altitude.*
8. *Departure airport.*
9. *Route of flight and destination airport.*
10-18. These fields include any items that may be specified in the facility directives, including actual departure time, departure runway, or any other pertinent information. Standard symbols have been developed for use in these situation.

The Central Traffic Flow Management Unit in Washington allows for the projection of congestion based inclement weather. This data is used to determine if a "gate hold" is required to restrict congestion that cc at destinations. The gate hold is preferred over being placed in an airborne holding pattern at the destinati savings.

This will be similar for AHS—the sooner traffic information can be known, the more efficiently the system can operate.

The assignment of a unique transponder code allows ATC to identify discrete aircraft in the system, thereby allowing ATC to anticipate routing for each aircraft.

Takeoff (Ground and Local Control)

***Comparable AHS Operation*—Enter into System**

Before a pilot radios the Control Tower for taxi and takeoff instructions, he will listen to the Automated Terminal Information Services (ATIS) broadcast. ATIS is a tape, updated at 5 minutes to the hour, which describes the ambient conditions, including:

- Temperature and dew point
- Barometer setting
- Wind speed and direction
- Visibility conditions
- Weather conditions (e.g., rain, snow, haze, *etc.*)
- Runways in use and radio frequencies for contacting Ground and Local controllers
- All “other” pertinent data such as Notice to Airmen (NOTAMs)

The ATIS broadcast is updated more frequently if there is a significant change in weather conditions (e.g., wind speed or direction, or barometer setting). ATIS broadcasts are given alphabetic identifiers, such as A-Alpha, B-Bravo, C-Charlie, so that the pilot and controller can verify that the pilot has the latest data.

When the pilot is ready to taxi, he will select the appropriate radio frequency and call Ground Control and supply the following information:

- Aircraft identification
- Location
- Request departure runway
- ATIS information

Below is an example of this transmission type:

> *Aircraft*—"Minneapolis Ground Control, this is Honeywell 123 at Gate 25, request taxi to 11 Left, have information Alpha."
>
> *ATC*—"Honeywell 123, Ground, taxi to 11 Left via charlie inner and alpha (taxiways), hold short of runway 4 (the aircraft must hold short of crossing this runway until cleared to by the Ground controller)."

The *Ground controller* will then provide a taxi routing to the departure runway, including any restrictions such as runway crossings.

The importance of unambiguous communication in safety critical situations is a lesson for AHS.

In the Control Tower the *Ground* and *Local controllers* must coordinate airport surface movement. The *Local controller* has authority over the use of active runways so the *Ground controller* must check with him to authorize any movement (aircraft or vehicle) across an active runway. All clearances provided by ATC must conform to the Air Traffic Controller's Handbook (FAA document 7110.65 version F, generated by the Air Traffic Operations Service). The standardization of phraseology is important in minimizing ambiguity that might arise through verbal interactions between ATC and controlled aircraft.

AHS parallel—Traffic Management Units at entry and exit nodes will have very different form and function than en-route TMUs.

When the aircraft is in position and ready for takeoff, the pilot will select the frequency for the *Local controller* to request permission to take off. The *Local controller* will then clear the pilot to taxi into position on the active runway and then take off. The *Local controller* is responsible for ensuring safe separation standards between aircraft landing and taking off. These standards are listed below.

Minimum Runway Separation Distances
When only Category I aircraft are involved „ 3,000 feet When a Category I aircraft is preceded by a Category II aircraft „ 3,000 feet When either the succeeding or both are Category II aircraft „ 4,500 feet When either is a Category III aircraft „ 6,000 feet
Category I „ Light-weight, single-engine, personal-type propeller driven aircraft. (Does not include higher performance, single-engine aircraft such as the T-28.) **Category II** „ Light-weight, twin-engine, propeller driven aircraft weighing 12,500 pounds or less, such as the Aero Commander, Twin Beechcraft, DeHavilland Dove, Twin Cessna. (Does not include such aircraft as a Lodestar, Learstar, or DC-3.) **Category III** „ All other aircraft such as the higher performance single-engine, large twin-engine, four-engine, and turbojet aircraft.

The *Local controller* will provide initial takeoff instructions, such as:

> ATC—“Honeywell 123, cleared to take off runway 11 Left, maintain runway heading, climb and maintain 4,000 feet, contact Departure on 123.05.”

The following lists technologies that aid the *Local* and *Ground controllers*.

Functional Requirement	Equipment	Technology
Two-Way Communications	Radio	VHF Radio
Surveillance	ASDE-3* (Airport Surface Detection Equipment)	Radar
Conflict Prediction	AMASS* (Airport Movement Area Safety System)	Trajectory Predicition
Integrated Flow Control	ASTA* (Airport Surface Traffic Automation)	TBD

**Future Implementation*

Climb (TRACON Control)

***Comparable AHS Operation*—Transition from Manual to Automated Control**

The *Departure controller* works in a windowless room in the Terminal Radar Approach Control (TRACON) facility. The controller identifies the aircraft on a Plan-View Display (PVD). The pilot will select the Departure control radio frequency and report his identity and altitude:

AHS parallel—confirming positive control

> *Aircraft*—"Minneapolis Departure, this is Honeywell 123, out of 1.1 (current altitude of 1,100 ft) for 4 (thousand, cleared-to altitude)."

When the *Departure controller* identifies the aircraft on the PVD, he will reply and (usually) modify the climb clearance:

> *ATC*—"Honeywell 123, radar contact, turn right heading 245 degrees, climb and maintain 8,000 (new clearance altitude)."

AHS parallel—vehicle "hand-offs" between Link and/or Sector controllers

When the ATC tells an IFR flight they have "radar contact," they are assuming responsibility for ensuring separation standards. The *Departure controller* will continue to issue modifications to the SID (Standard Instrument Departure) as required. Finally, the aircraft will reach the boundary of the TRACON sector and a hand-off to the ARTCC (Air Route Traffic Control Center) will be initiated. The *Departure controller* will advise the pilot to contact the ARTCC and provide the appropriate radio frequency:

> *ATC*—"Honeywell 123, contact Minneapolis Center on 122.75."
>
> *Aircraft*—"Departure, Honeywell 123 contact Minneapolis Center on 122.75, thank you, have a good day."
>
> *ATC*—"Good day."
>
> AIRCRAFT CHANGES FREQUENCY
>
> *Aircraft*—"Minneapolis Center, Honeywell 123 with you climbing out of 14,000 (current altitude) to 25,000 (current cleared-to altitude)."

En-Route Flight (ARTCC Control)

***Comparable AHS Operation*—Trip Progress Monitoring and Velocity and Steering Regulation.**

There are 20 Air Route Traffic Control Centers (ARTCC) around the continental United States. Each center is subdivided into five or six areas. Each area is subdivided into six to eight sectors. Each sector describes a volume with discrete lateral and vertical boundaries. Low-altitude sectors cover the ground to 18,000 feet (above sea level) and high-altitude sectors begin at 18,000 feet and extend to the top of the Positive Control Area (60,000 feet). It can be the case that there are sectors with identical lateral boundaries, but differ only in the altitude (vertical) dimension.

***Comparable AHS Operation*—Off Vehicle Monitoring**

As the aircraft continues its journey, it will pass through several sectors within a given center. As the aircraft passes from one sector to another, ATC personnel will "hand off" the aircraft to other controllers within the same facility. This may seem odd to those monitoring the radio transmissions between the controlling facility and the aircraft; an example follows:

> *ATC*—"Honeywell 123, Minneapolis Center, contact Minneapolis Center on 124.25."
>
> *Aircraft*—"Minneapolis Center, Honeywell 123, contact Center on 124.25, thank you have a good day."
>
> *Aircraft*—"Minneapolis Center, Honeywell 123 with you at Flight Level 370."
>
> *ATC*—"Roger Honeywell 123, radar contact."

AHS parallel—jurisdictional variations in procedures.

Every sector has one to three controllers working to ensure separation standards are maintained. The *Radar controller* works using a radar plan view display (PVD) to assign altitude, heading, or airspeed changes to ensure separation standards and in accordance with preestablished operating procedures (letters of agreement and facility directives). To support the Radar controller during busy periods a *Radar associate/nonradar controller* updates the flight progress strips (FPSs) to reflect the current clearance (position, altitude, heading, and route of flight) of each aircraft under positive control in that sector. The *Radar associate/nonradar controller* must be prepared to assume separation responsibilities in case of primary radar failure. To support the controllers at each station are *Flight data controllers* whose primary responsibility is to distribute FPSs to the appropriate sector controller.

When congestion at destination airports restricts the ability of the airport to accept incoming flights, an in-flight hold is required. Holding patterns are "usually" marked at discrete intersections along jet (high-altitude) and victor (low-altitude) airways. A standard holding pattern is characterized by right-hand turns that take a minute to reverse direction 180_. The length of each leg is usually specified by ATC; longer legs are used when the holding pattern must accommodate multiple aircraft.

Transoceanic Flight (ARTCC Control)

***Comparable AHS Operation*—En-route operations including Lane Changing, also inter-city operations.**

To establish common "rules of the road" for operations between countries and across the world's oceans, the International Civil Aviation Organization (ICAO) was formed. This organization developed standards in 1944 and periodically will update those standards (usually as new technology developments enable new functionality) at Air Navigation conferences.

AHS parallel—accommodating variably equipped vehicles.

The most heavily traveled oceanic environment is the North Atlantic. There are two types of airways used to traverse the Atlantic: low-altitude and minimum navigation performance specifications airspace (MN SPA). Low-altitude airways are one-way conduits that skirt close enough to land that terrestrial navigation aids can be used (these navaids have a line-of-sight requirement). The other type of airway allows for much more flexible routing but requires specific equipment be installed and operational on the aircraft. The separations are reduced for aircraft using the MNSPA.

Separation Standards

Vertical : Up to and including FL290 1,000 ft separation required
Above FL 290 2,000 ft separation required
Supersonic above FL450 must be separated from non-supersonic by 4,000 ft

Lateral : 120 nm separation
Above FL275 separated by 60 nm

Longitudinal : 10 min separation between turbojet aircraft
30 min separation between non-turbojet aircraft
10 min separation between Supersonic aircraft

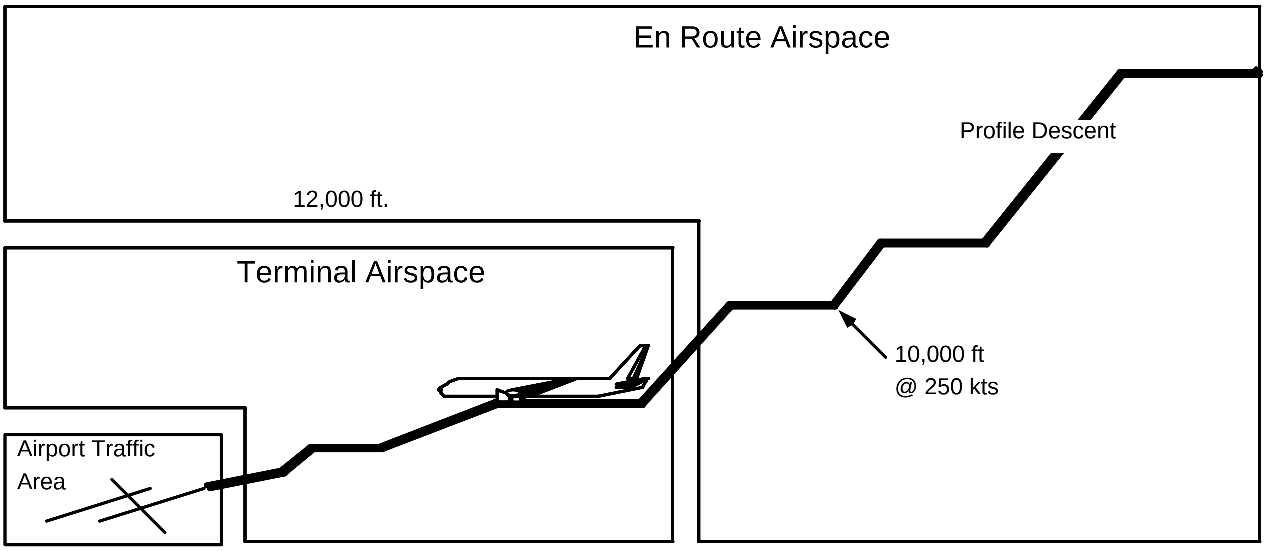
Aircraft flying over the Atlantic or Pacific are currently separated by controllers using nonradar procedures. The aircraft use high-frequency (HF) radio to communicate with controllers at prespecified intervals. HF radio, while not requiring a direct line of sight ,as does VHF, is susceptible to atmospheric and cosmic interference, resulting in significantly poorer transmission quality (which can be unintelligible at times).

Descent and Approach (TRACON Control)

As an aircraft nears a destination, it will begin a descent. For fast, high-flying commercial aircraft, this descent will begin while under ARTCC control.

Aircraft—"Los Angeles Center, Honeywell 123, requesting descent to FL250."
ATC—"Honeywell 123, descend at pilot's discretion and maintain FL250 (meaning whenever the pilot wishes to begin the descent)."

Frequently, in congested terminal areas, a specific series of speeds and altitude restrictions is part of a published descent procedure (Profile Descent). This is done to consolidate incoming aircraft along the same physical path and restrict speed so that the aircraft will maintain the same relative position with respect to one another.



In the terminal area, there are published approach procedures as well.

***Comparable AHS Operation*—Exit System, Transition from Automated to Manual Control**

Final Approach and Landing (Local and Ground Control)

When the aircraft is instructed to contact the control facility regulating traffic into and out of the airport, the pilot should already have listened to a recorded broadcast of local weather and airport conditions called the Automated Terminal Information Service (ATIS). ATIS eliminates the need for controllers to repeat local conditions (winds, altimeter setting, runways, and radio frequencies in use) to each aircraft.

Aircraft—"Los Angeles Approach, this is Honeywell 123, with you at 9,000 on the CIVET Profile Descent with information Tango (the ATIS identifier always has an identifier, A-Alpha, B-Bravo, *etc*.)."

The *Approach controller* will have a copy of the aircraft's flight plan, and factors in traffic to provide the most expeditious clearance available. The *Approach controller* provides authorization to enter the Terminal Area.

ATC—"Honeywell 123, maintain 250_ (runway heading) reduce speed to 170 knots, cleared for the approach, contact the Tower on 123.05."

The aircraft the contacts the control tower at the destination airport to obtain landing clearance.

Aircraft—"Los Angeles Tower, this is Honeywell 123, with you on approach for Runway 25R."

ATC—"Honeywell 123, cleared to land Runway 25R, wind is 240_ at 12 (knots), contact Ground Control on 119.5 after landing."

Once the aircraft has landed and pulled off the active runway, the pilot will request a ground clearance to the appropriate gate.

Aircraft—"Los Angeles Ground, this is Honeywell 123, off to the right of Runway 25R, requesting ground clearance to Gate 73."

ATC—"Honeywell 123, cleared to Gate 73 via Oscar and the Inner (taxiway names that are displayed on airport layout diagrams)."

Determine Visibility (Effect on Landing Minimums)

***Comparable AHS Operation*—Exit System, Transition from Automated to Manual Control**

The most difficult aspect of aviation is landing in an environment that has restricted vision (i.e., a low cloud ceiling, haze, or fog). Special training and navigation integrity requirements are needed for landing operations under conditions of low visibility. The following figure lists the cloud ceiling (decision height) and runway visibility (RVR) standards for landing criteria.

INTERNATIONAL CIVIL AVIATION ORGANIZATION (ICAO) STANDARDS FOR LANDING			
Category	Decision Height, ft	RVR, ft	Time to Touchdown, sec
VFR	600		
Cat I	200	1800-2400	22-27
Cat IIA	150	1600	17-20
Cat IIB	100	1200	12-15
Cat IIIA	50	600-700	4-7
Cat IIIB	see to taxi	150	0
Cat IIIC	zero/zero	0	0

In Europe, where low-visibility conditions are more common than in the United States, there was a push to automate the landing operationAutoland was developed by the British and has been in successful operation since the mid-1960s. However, there is a tradeoff between the cost-effectiveness of keeping flight crews trained to proficiency, as well as the expensive maintenance to keep the high-integrity navigation systems up to satisfactory criteria, versus simply diverting to an alternative destination with acceptable landing conditions.

REFERENCES

1. *The ICAO CNS/ATM Systems: Coping with Air Traffic Demand*, Appendix B to the Report on Agenda Item 8, FANS(II)/4-WP/82.

2. *Current Market Outlook—World Market Demand and Airplane Supply Requirements*, Boeing Commercial Airplane Group, 1992.

3. "The Strategic Plan for IVHS in the United States," IVHS America (1992), IVHS America Report No. IVHS-AMER-92-3, Washington, D.C.

4. "Sketch of an IVHS Architecture," Varaiya, P. and Shladover, S., Institute of Transportation Studies Report UCB-ITS-PRR-91-3-PATH, University of California, Berkeley, Oct. 1990, revised Feb. 1991.

5. "Human Factors Design of Automated Highway Systems: Fisrt Generation Scenarios," Tsao, H.S. J., Hall, R.W., Shladover, S.E., Plocher, T.A., Levitan, L.J., Federal Highway Administation Report FHWA/RD-93/???, Federal Highway Administration, Washington D.C., October 1993.

6. "Human Factor Design of Automated Highway Systems: Comparable Systems Analysis," Levitan, L., Llaneras, R.E., DeMers, R.E, Plocher, T.A, Federal Highway Administration Report FHWA/RD-94/????, Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia.

7. "The Effects of Regulation 25.1309 on Aircraft Design and Maintenance," Gilles, D.L., SAE Technical Paper 83140b, Aerospace Congress & Exposition, Long Beach, CA, 3-6, Oct. 1983.

8. "Function Criticality, Allocation and Mechanization for AHS Health Management Precursor System Analysis," Meisner, J., Frazzini, R., Funk, H. Federal Highway Administration Report FHWA/RD-93/???, Federal Highway Administration, Washington D.C., April 1994.

9. "Human-Centered Aircraft Automation: A Concept and Guidelines," Billings, C.E., NASA Technical Memorandum 103885, 1991.

10. A Review of Research Related to Automated Highway Systems (AHS), Lansky, T.A., Interim Reoprt for Contract DTFH61-93-C-00189, FHWA, Oct. 1993.

11. "Standards Main Hurdle to New ATC Technologies," Nordwall. B.D., Aviation Week & Space Technology, May 16, 1994.

BIBLIOGRAPHY

Federal Aviation Administration
FAA Order 8400.10, Air Transportation Operation Inspector Handbook.
FAA Notice 8110.47, Airworthiness Approval Of Global Positioning System (GPS) Navigation Equipment For Use As A VFR And IFR Supplemental Navigation System.
Technical Standard Order (TSO) C-129, Airborne Supplemental Navigation Equipment Using the Global Positioning System (GPS).
Advisory Circular 20-130A, Airworthiness Approval of Navigation or Flight Management Systems Integrating Multiple Navigation Sensors.
Advisory Circular 90-45, Approval for Area Navigation Systems for use in the U.S. National Airspace System.
Advisory Circular 90-76, Flight in Oceanic Airspace.
Advisory Circular 90-79, Recommended Practices and Procedures for the Use of Electronic Long-Range Navigation Equipment.
Advisory Circular 90-82B, Direct Routes in the Conterminous United States.
Advisory Circular 91-49, General Aviation Procedures for Flight in North Atlantic Minimum Navigation Performance Specification Airspace.
Advisory Circular 120-33, Operational Approval of Airborne Long-Range Navigation Systems for Flight Within the North Atlantic Minimum Navigation Performance Specification Airspace.
Radar Installation Criteria, 1993.
Society of Automotive Engineers
Data Link Development at the FAA Technical Center,, paper # 922026, N. Talotta.
Journal of the Institute of Navigation
Safe Separation In Controlled Flight, Spring 1974, J. M. Holt.
Pilotage Error And Residual Attention: The Evaluation Of A Performance Control System In Airborne Area Navigation, Fall 1973, S. N. Roscoe And E. F. Kraus.
Royal Institute of Navigation
Aircraft Separation Assurance: Systems Design, Vol. 36.
Air Traffic Control Separation Standards and Navigation, Vol. 24.
Analysis of Long-Range Air Traffic systems, Separation Standards III, Vol. 19, P.G. Reich.
Separation Standards and Aircraft Wander, Vol. 19, R. N. Lord.
Transportation Research
An Analytical Method for Aircraft collision Risk Estimation, 1986, S. Hockaday and A. Chatziioanou.
Departments of Defense and Transportation
1992 Federal Radionavigation Plan.