Using Advanced Avionics To Improve Air Traffic System Capacity and the Prospect of Public Funding for Airline Equipment Acquisitions

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The ability to accommodate the continued growth of air travel by expanding the associated landside infrastructure is constrained by environmental factors and financial deficits. By application of the latest technology to airplanes, however, system improvements that can bring substantial reductions in public-sector costs are possible. How to fund such beneficial improvements is a difficult question. The need for better data than have been developed on air traffic system capacity, the potential benefits of new technologies, and the need to reorder some development program priorities are described. A rationale for evaluating the prospect of public funding for airline equipment acquisitions is suggested. A key element of the approach to achieving these objectives is the presentation of data developed internally by several airlines individually (some of which are proprietary and are presented with sources available on request) and by individual industry observers and authorities. These data are useful in estimating the magnitude of findings that might be expected if research is conducted on a system level.

Constraints placed on the air traffic system (ATS) as a result of airway system design and low-visibility operating restrictions became widely recognized in the late 1960s. Many of these advances were developed to address, in particular, delays generated by ATS capacity limits. A common feature of these efforts was their sponsorship almost exclusively by the private sector. Airlines funded the technology advances, in effect, through their ongoing purchases of new airplanes and equipment at increasingly higher prices.

New developments were also undertaken occasionally by the private sector in an attempt to circumvent the limitations of the established system. One example is the use of Flight Management System (FMS) technology to improve system capacity, which resulted in the establishment of some 80 FMS approaches in the United States and was entirely an airline initiative.

The air carrier industry is now evolving toward satellite-based navigation, which is, in effect, a radio navigation system. It offers greater accuracy and reliability than past systems and makes possible, for the first time, decommissioning of virtually the entire ground-based navigation infrastructure. The ability to implement systemwide direct routings will depend, as in the past, on changes to the air traffic control (ATC) system—in philosophy as well as in structure. The potential high accuracy of the satellite-based system also makes its application possible as the basis for approach operations, conducted with advanced optical systems, in which low-visibility landing operations may be conducted without the extensive airport infrastructure improvements otherwise needed to support such operations. (Development of the related optical technology is not being adequately supported or advanced by the federal government.)

Substantial financial benefits are possible from satellite-based operations and will accrue to the nation's economy as well as to air carriers. Decommissioning the groundside navigation infrastructure and avoiding capital outlays for airport improvements constitute a major benefit to the public sector, made possible by relocating navigation and ATC functionality from the ground to the airplane. Doing so, however, may place an intolerable financial burden on airlines, whose bleak financial circumstances at least partly reflect their continuing efforts to recover from the destabilizing effects of airline deregulation. It is in this context that public funding for initial equipment acquisitions by air carriers should be considered. Concurrently, development programs in process should be reviewed and discontinued where they are found to be inferior to the capabilities of satellite-based navigation or optical landing technology. All available funding can then be focused on the most beneficial programs. The potential benefits to airlines exceed industry losses and are, therefore, central to the health of the industry.

FAA has launched a broad range of initiatives intended to exploit the many possibilities offered by a global navigation satellite system (GNSS), including improved oceanic and domestic en route navigation, approach and landing, and airport surface operations. Domestic GNSS applications are being increasingly emphasized, and FAA schedule projections for GNSS implementation are being revised favorably. A system-level effort should now be initiated to measure the financial, economic, and social benefits of the new technology base for domestic air transportation. In this manner, the returns to society on the substantial investment needed—one which the airlines are not in a position to make by themselves—can be evaluated.

Airline costs reside in such areas as excessive fuel burn, crew pay, and excessive aircraft overhead (technical and administrative) per flight segment. Costs to the economy are in productivity losses, excessive use of resources (fuel, etc.), higher transportation costs (fares), and, where navigation technology is concerned, financial support of an obsolete groundside infrastructure that demonstrates poor reliability, and for which low production quantity components are becoming prohibitively expensive.

Constraints on ATS capacity are considered the most serious problem facing the future of U.S. commercial aviation. Slowdowns in the system adversely affect both domestic and international air

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commerce and are a detriment to economic growth. Congestion and delays in the United States have been estimated to cost the domestic economy in excess of $10 billion annually (*1*). On an international scale, it has been estimated that a delay of 1 min/hr for a single Boeing 747 costs the world's economy $1 million per year (*1*).

FAA efforts to advance ATC automation have focused on the Advanced Automation System (AAS), which may need redirection of its technical and philosophical components to accommodate system changes now on the horizon.

Policy related to the navigation technology factor, as a constraining mechanism on the air traffic system, is the focus of this paper.

CURRENT ATC SYSTEMS

En route Operations

The primary radio navigation system in the United States is a network of airways defined by VOR ground stations. The principal shortcomings of the system are indirect routing; the feeder-arterial quality of its structure, which funnels traffic onto crowded airways and leaves much available airspace unused; and angular inaccuracy (the relationship between distance from a station and positional accuracy).

Before availability and acceptance of the Global Positioning System (GPS), FAA's approach to improving the en route structure focused on modernizing ATC equipment and updating procedures to streamline operations within the constraints of existing system design. With GPS has come an awareness of the air traffic management (ATM) concept. Use of GPS for direct navigation can only have a meaningful impact on system capacity if it is supported by an ATM structure designed to accommodate direct navigation on a system level.

Terminal Area and Approach Operations

A number of constraints related to terminal area navigation currently serve to limit the amount of traffic that can be accepted into a terminal area before measures are introduced that produce delays. The inferior accuracy and slow sweep speeds of existing terminal area surveillance radar systems contribute to conservative spacing practices. Local area environmental policies and ordinances lead to suboptimum routings. Some routings are optimized on the basis of landmark recognition. Aircraft that rely on VOR or ILS signals for terminal area navigation must abandon such routings in instrument conditions. Also, VOR and ILS signals are subject to interference from atmospheric and geographical phenomena, including multipath anomalies.

Development of the MLS was, in part, an attempt to deal with terminal area capacity problems. The system enabled curved or segmented approaches under MLS guidance, as a means to address environmental concerns and the ability to retain irregular approach paths in instrument conditions. MLS also provided vertical guidance and a much higher degree of immunity from interference than that afforded by VOR or ILS. MLS was capable of providing sufficient accuracy for Category IIIb approach operations. The cost for each runway-end installation of MLS was estimated at approximately $1 million.

FAA is now directing and participating in efforts to develop GPS for precision approach operations comparable with those possible with MLS. Updated primary radar systems with trend projection and conflict alert software are still planned for use in enhancing terminal area operations.

Airport Surface Operations

Current plans to improve ATC's ability to deal with surface traffic are based on a new primary radar system that offers greater accuracy and faster sweep-display update rates, known as ASDE-3 (airport surface detection equipment). ASDE-3 radar systems will cost approximately $4.5 million per installation.

En Route Capacity

The elements of the existing en route system that most affect capacity include the structure of the airways system and the accuracy of existing navigational aids, in combination with the characteristics of ATC surveillance equipment.

Airways System Structure

Tremendous capacity improvements and financial savings are possible in direct routings and the ability to fly at optimum altitudes. The fuel penalty for flying at other than optimum altitudes has been estimated to be in excess of $150 per hour. A Boeing 747, for example, which operates 3,600 hr per year, could reduce its fuel burn by $540,000 annually (*2*, p. 12).

United Airlines estimates that using satellites for direct routing in domestic operations might reduce flight times by 1 percent and 3 million mi per year (*3*, p. 53). United's domestic departures in 1992 (720,592) (*4*, p. 12) comprised 10.5 percent of the total number of U.S. Air Transport Association (ATA) member domestic departures (6,866,325) (*4*, p. 2) of that year. If the relationship of United's departures to the ATA-member total is extended to miles flown, it can be estimated that domestic route miles flown by ATA-member airlines might be reduced by more than 28 million per year as a result of direct routing supported by GPS.

Another major airline estimates that direct routing of domestic flights will save almost $340 million annually as a function of direction of flight and flight at optimum altitudes and winds (see Table 1). [These data were provided by an airline representative at a committee meeting of the Air Transport Association in 1994. The airline (Airline A) requested that its identity not be published but agreed to be identified as the source upon specific request. Source of the data will be provided upon request.] This airline also estimates the value of productivity gains that would be realized as a by-product of operationalizing the savings shown in Table 1 at $1.6 billion in annual profit.

If the savings in Table 1 are applied proportionally to other U.S. (ATA-member) airlines on the basis of annual departures, the resultant potential domestic industry savings approach $4 billion.

A third major airline (*6*) has estimated savings and contributions to increased system capacity on the basis of modeled city-pairs (see Table 2). [These data were provided in 1994 by an airline representative who requested that the airline identity not be published. The airline (Airline B) agreed to be identified as the source upon specific request. Source of the data will be provided upon request.]

Table 2 indicates that the largest potential savings, as a percentage of total trip resources, will be realized on shorter stage lengths. Savings for longer trips are, however, significant.

TABLE 1 Airline A Losses due to Inefficient Routing and Altitude, Domestic U.S. Operations, 1993

	Quantity	Unit Cost	Total
Enroute Losses[1]			
Indirect Routes	4,995,482	$60	$299,728,920
Delays[2]	362,341	$60	$ 21,740,460
Cruise Inefficiency[3]			
Altitude, Winds	25,750,000	$0.66	$ 17,098,000
Total:			$338,567,380

[1]Enroute losses are measured in minutes.
[2]Includes execution and delays.
[3]Cruise inefficiency is measured in gallons.

Airline B extended the Table 2 data to its entire fleet and domestic route structure. It estimated that a systemwide fuel savings of 8 percent was reasonable—$117 million annually, at current prices. Time savings were also estimated at 8 percent and expressed in terms of aircraft variable cost at $155 million. Additional ATC-related savings were calculated, which included the expected effects of reduced delays (ground and air), conducting approach, landing, and taxi operations under low-visibility conditions at the same rates as under visual conditions, and the elimination of speed restrictions below 10,000 ft. These measures are expected to produce an additional $230 million, bringing the total to more than $500 million annually.

Navigation and Surveillance Accuracy

The basic navigational accuracy of GPS-derived position information is superior to that of VOR-based signals. En route accuracy currently supported for GPS is on the order of ±100 m, with substantial improvements possible. In addition, GPS navigation data are not angular and are therefore not position dependent.

Automatic dependent surveillance (ADS) describes a system by which GPS-derived position information (with additional aircraft and environmental data, as desired) is data-linked via satellite or terrestrial connections to ATC and displayed on a conventional azimuth-oriented display, referred to as "pseudo-radar." The implicit accuracy of ADS is extremely high and independent of the angular distance inaccuracies associated with primary radar.

In combination, the navigational and surveillance accuracies of GPS and ADS far exceed those associated with VOR and primary radar and can be expected to have a substantial effect on U.S. air traffic system capacity by making reduced separation standards possible in en route operations. Current development work aimed at implementing ADS as early as possible has only recently included domestic applications and oceanic operations.

One recent measure is a proposal by FAA to fund $200 million for the acquisition of ADS broadcast devices by the general avia-

TABLE 2 Airline B Estimated Savings from Direct Routing by City-Pair

	City-Pair			
	A	B	C	D
Current Distance[1]	218	1,758	888	749
Potential Distance[2]	160	1,686	857	704
Savings (nm)	58	72	31	45
Savings (%)	27	4	3	6
Current Enroute Time[3]	44	238	130	108
Potential Enroute Time[4]	32	228	126	102
Savings (min)	12	10	4	6
Current Fuel Burn (lbs)	8,580	38,270	21,300	18,300
Potential Fuel Burn (lbs)	6,107	36,470	20,200	16,650
Savings (lbs)	2,473	1,800	1,100	1,650
Potential Fuel Savings (%)	29	5	5	9
Potential Time Savings (%)	26	4	3	6

[1]Current distance is the average actual distance flown due to current routing practices, expressed in nautical miles.
[2]Potential distance assumes optimum (direct) routing, expressed in nautical miles.
[3]Current enroute time is the average actual time required for the flight due to current routing practices, expressed in minutes.
[4]Potential enroute time assumes optimum (direct) routing, expressed in minutes.

tion fleet, based on recognition of the fact that a system in the United States based on ADS surveillance will not work without the full participation of the general aviation community.

American Airlines has estimated that reduced flight times made possible as a result of surveillance accuracies associated with ADS, including both oceanic and domestic operations, are expected to save $5 million in fuel costs (at current prices) and $4 million in crew costs. RTCA has estimated that improvements related to ATC's more precise knowledge of aircraft position, from capabilities such as ADS, could save airlines some $13.2 billion between 1995 and 2015 (*3*, p. 53).

Terminal-Airport Capacity

For air carrier operations, from the perspective of navigational and surveillance accuracy, airport capacity is most affected by configurational characteristics of the runway and taxiway system, procedures affected by environmental ordinances, and facilities enabling operations in conditions of low visibility—in the air and on the ground.

Runway-Taxiway System

Techniques used to model runway capacity have evolved over the years from probabilistic to more simulationlike.

For computing the effects of runway interdependency in the case of parallel runways, operations in instrument meteorological conditions (IMC) may be classified as either "independent parallel" or "dependent parallel" approaches. In general, independent parallel approaches can be conducted in IMC on parallel runways in the United States that are spaced at least 4,300 ft apart. For parallel runways that are spaced closer than 4,300 ft, dependent parallel approach operations are conducted in which lateral (diagonal) spacing between aircraft on parallel approach paths and longitudinal (in-trail) spacing for aircraft on approach to the same runway must be maintained. Airport capacity will be increased where it is possible to maintain independent runway approach operations despite reductions in visibility below visual conditions (visual meteorological conditions).

Where parallel runways that operate in the dependent case can be changed to operate in the independent case, a capacity improvement from as low as 29 operations per hour to as much as 57 operations per hour can be achieved, an increase of almost 97 percent.

The Aviation System Capacity Plan has determined that of the top 100 U.S. airports, 30 could benefit from improved capacity as a result of independent parallel instrument flight rules (IFR) approaches, 18 could benefit from dependent parallel IFR approaches, 53 could benefit from dependent converging IFR approaches if a prospective converging runway display aid were used, 32 would gain capacity benefits from independent converging IFR approaches, and 13 would gain increased capacity from triple IFR approaches (*5*, p. 7-2).

The most significant improvements to airport capacity in this area are currently envisioned to be as a result of adding new runways, extending existing runways, and arranging spacing to allow independent arrival and departure streams. Capacity increases are estimated at between 33 and 100 percent, depending on airport configuration (*5*, p. 2-13). At the same time, it is acknowledged that "significant capacity gains can be achieved at airports with closely spaced parallel runways if the allowable runway spacing for conducting independent parallel instrument approaches can be reduced" (*5*, p. 5-5). Further, "analysis and demonstrations have indicated that the separation between parallel runways could be reduced if the surveillance update rate and the radar display accuracy were improved, and special software was developed to provide the monitor controller with alerts" (*5*, p. 5-5). This approach to improving airport capacity through reduced runway separation standards relies on conventional radar surveillance, with a faster update rate to reduce the time required for ATC to perceive a potential conflict, aided by conflict alert software.

Independent parallel instrument approaches can currently be conducted at approximately 15 airports in the United States where runway separation is at least 4,300 ft. Building triple parallel approach facilities would increase capacity by 50 percent. Building quadruple parallel approach facilities would increase capacity by 100 percent. Using existing radar technology, but with an azimuthal ccuracy of 5 milliradians and an update rate of 4.8 sec, this would require a 5,000-ft runway separation (*5*, p. 3-4).

Table 3 gives capacity differences for selected runways (data provided by FAA). Table 4 gives estimated savings, in time and dollars, associated with independent parallel operations at the airports described in Table 3 (data provided by FAA).

In determining the classification of approaches at a given airport/runway system as dependent or independent, computer simulations and flight simulator sessions are run in place of mathematical modeling. Diagonal spacing is defined at maximum in coordination with in-trail spacing requirements. Key variables used to test approach operations for classification as independent include the time and airspace required for "blunder" detection and coordinated corrective action by ATC and the flight crew. The time sequence includes (a) commission of the blunder (e.g., a sudden, inappropriate heading change), (b) recognition of the blunder by ATC, (c) communication of corrective measures by ATC to the errant flight crew, and (d) execution of corrective control inputs by the flight crew.

As a means for improving azimuthal accuracy, FAA is testing a final monitor aid that will provide accuracy within 1 to 2 milliradians, but still with only a 4.8-sec update rate. FAA is also testing a precision runway monitor (PRM) radar with high azimuth and range accuracy and update rates of 0.5 to 2.4 sec. Capacity improvements are expected as a result of these systems, supporting independent approaches to parallel runways separated by 3,400 ft, and down to as low as 3,000 ft (*5*, p. 5-5).

One technology option exists, however, with the potential for changing the variables used and process itself, and should be explored. This option offers greater accuracy, is less expensive to implement and support, and is based on combining GPS approach navigation with ADS surveillance and GPS-based collision avoidance cockpit displays.

By enhancing the accuracy and update rate of existing collision avoidance systems with nonangular GPS-based data, the accuracy of the TCAS display can support its use as the basis for colocating the blunder detection function in the cockpit. The time required for blunder detection by ATC would then be virtually eliminated (relegated to backup, coordination, and advisory), and the requirement for initial communication to the flight crew by ATC would be replaced with immediate recognition and action by the flight crew. (ATC would remain in the information loop for coordination of other traffic.) This methodology can be implemented at significantly lower cost than the PRM (radar-based) methodology in

TABLE 3 Potential Capacity Improvements Using Existing Runways in Arrivals per Hour, Dependent Versus Independent Operations

Airport	Runways	Centerline Spacing (ft)	Dep. Parallel Capacity	Indep. Parallel Capacity
Dallas Love	31R/31L	2,975	35.9	52.8
Baltimore	10R/10L	3,500	37.0	52.0
Houston	8L/8R	3,500	50.8	76.2
Kennedy	4R/4L	3,000	36.9	49.0
Portland, OR	28R/28L	3,100	35.5	52.6
Minneapolis	11R/11L	3,380	35.5	49.2
Phoenix	8R/8L	3,400	34.6	48.4
Memphis	36R/36L	3,400	35.2	49.2
Salt Lake City	16R/16L	3,500	36.2	50.8
Raleigh	5R/5L	3,500	35.4	49.2
Detroit	3L/3C	3,800	36.6	50.2
Ft. Lauderdale	27R/27L	4,000	34.7	48.0
AVERAGE CAPACITY			37.0	52.3
OVERALL CAPACITY INCREASE			41.3%	

development, both in initial investment and in long-term support. Perhaps most important, it has the potential to modify approach evaluation methods, yield capacity increases greater than those currently anticipated by conventional methods, and improve operational safety.

Low-Visibility Operations—Airborne

Of all delays greater than 15 min, 66 percent are caused by weather (27 percent by terminal volume). These delays are largely the result of instrument approach procedures that are much more restrictive than visual procedures (*5*, p. 1-15) and result in restriction of the airport's capacity. Of some 12,000 airports in the United States, only 40 are Category III equipped to support operations in visibility conditions less than those associated with basic IFR. (Europe has some 170 Category III capable airports.) One airline estimates its direct annual cost of diversions, cancellations, and passenger misconnects related to weather at $28.9 million (source of data supplied on request).

The use of GPS for approach and landing guidance in conditions below Category I, such as Category II (runway in view at 100 ft, 1,200 ft or less visibility) and Category III (potentially all the way to 0/0), is currently in the development stage. There is little doubt

TABLE 4 Estimated Annual Savings, Independent Parallel Approaches, 2000

Airport	Annual Delay Savings (hours)	Annual Delay Savings ($ millions)
Dallas Love	24,820	$ 39.9
Baltimore	15,768	25.4
Houston	6,534	10.5
Kennedy	5,877	9.5
Portland, OR	438	0.7
Minneapolis	36,135	58.1
Phoenix	17,155	27.6
Memphis	62,014	99.8
Salt Lake City	17,776	28.6
Raleigh	66,065	106.3
Detroit	1,570	2.5
Ft. Lauderdale	2,628	4.2
TOTALS	256,780	$413.1

that GPS guidance adequate for Category III operations is technically feasible. Successful autolands have been demonstrated at Category IIIB standards without the use of pseudolites, kinematic phase tracking, or enhancement from other aircraft systems. Differential GPS (DGPS) correction uplinks with C/A code tracking and carrier phase smoothing algorithms only were used. Category III required navigation performance was met within comfortable margins using a NASA Boeing 737-100 (*6,* p. 1).

In support of current plans for enhancing system capacity through airport infrastructure improvements, FAA and airport capacity design teams identified 23 "delay-problem" airports (exceeded 20,000 hr of annual delay) in 1991, 17 of which are constructing or planning new runways or extensions. Since then, 33 airports were forecast to exceed 20,000 hr of annual delay by 2002, of which 25 now have plans for construction of new or extended runways. Some runway upgrades are planned to meet Category III requirements, but not all. Of the top 100 airports in the country (on the basis of number of departures), 62 have proposed new or extended runways. The cost of these efforts combined exceeds $7.7 billion (*5,* p. 7-3). Even if carried out, their effect on system capacity will be substantially less than is possible by technologically superior alternatives.

For example, the Lambert–St. Louis International Airport Capacity Enhancement Plan, completed in 1988, was designed to increase IFR capacity to VFR capacity (*5,* p. 4-3). Included among the recommendations were construction of one new runway, conversion of a taxiway to a runway, three taxiway extensions, relocation of a cargo area, installation of a Category III ILS, installation of new radar for surveillance of surface operations (ASDE-3), and relocation of the Air National Guard facility (*5,* p. C-55). The new Category III ILS makes additional approaches possible in low-visibility conditions only at a single runway end and applies only to airplanes and carriers equipped with and certified for autoland or head-up display (HUD) system operations. Older air carrier airplanes and regional operators cannot equip cost-effectively for these types of operations.

When simply substituting GPS for ILS, Category III operations continue to require runway system and geographical upgrades to support the sophisticated and expensive automatic landing systems, normally associated with only the newest and most expensive air carrier airplanes, or the advanced HUD. The use of HUD for manually flown operations to Category III minimums has been demonstrated through the in-service experience of Alaska Airlines (*7,* p. 27). HUD reduces the need for expensive autoland systems but still relies on the presence of the groundside Category III infrastructure.

There is a potential means by which Category III operations can be successfully carried out, with equal if not greater safety than in the past, while almost completely avoiding expensive runway upgrades and eliminating reliance on autoland operations. This approach can also enhance the use of older air carrier airplanes still in service and support the participation of operators using smaller aircraft, such as regional carriers. It is a system that can make it possible to execute approaches and landings in Category III conditions at Category I facilities. The system is the enhanced vision system (EVS) that, if successfully developed, can enable flight crews to see the runway environment through intervening clouds and fog.

The development of EVS technology, in combination with GPS-ADS and autoland operations, offers the possibility of either hand-flown or automatic approaches to Category III minimums, on Category I runways, independent of ground-based navigation aids, runway lighting and marking, and most geographical constraints. EVS is broadly accepted as a promising technology for monitoring GPS-based position. A number of industry experts are confident of its potential for accomplishing Category III landing operations at Category I facilities. Its potential for enhancing safety, improving system capacity, and making it possible to avoid billions in airport infrastructure improvements and upgrades clearly calls for priority for its evaluation and timely development.

The baseline requirement for an EVS system has been established as giving the flight crew the ability to execute a landing and rollout, either manually or through autoland, from an approximate position of Category I minimums (200′½) "regardless of prevailing atmospheric visibility" (*8,* p. 2). Specifically, the EVS operational requirement is to enable low-visibility operations to at least Category IIIA, on Category I runways, with visual identification of runway references in accordance with the requirements of FAR 91.175 (c)(3) (*8,* p. B1). Cost to the service provider (FAA) will be considerably less than existing precision landing systems, with much greater potential benefits. Cost to the user, however, could be as much as the theoretical retrofit of a fail-operational autoland system. In the case of regional airlines, prices in that range can exceed the value of the airplane (*9,* p. 58). If EVS technology is not made available for substantially less, neither regional airlines nor the majors will be able to afford it.

The findings of the Working Group on Enhanced and Synthetic Vision indicate that FAA does not have a current research and development effort on EVS technology in place and that it has a "requirement to promote safety and provide certification support for users and industry when such support is requested" (*8,* p. 2). It found that the industry wants FAA's participation, particularly in the area of human-machine interface, and that funding may also be required. Ultimately, the report stated that the FAA should "encourage, support, participate and enable, industry and users to proceed in an expeditious manner to safely and efficiently take advantage of this technology" (*8,* p. 3).

Low-Visibility Operations—Ground

It has been estimated that nearly 80 percent of all flights are delayed from 1 to 14 min in the taxi-in/taxi-out phase of flight (*5,* p. 5-1). For a Boeing 747-400, 15 min of unnecessary ground running time is worth $550 in direct operating costs (at current prices) (*2,* p. 12). United Airlines estimates the annual cost of departure delays at $100 million (*10,* p. 49). Another estimate indicates the annual cost of delays on the surface as follows: gate delays (due to flow control, ATC, or airport), 580,000 min with a value of $14.5 million; taxi delays (outbound and inbound), 7,300,000 min with a value of $256.8 million; a total of $271.3 million (source of data supplied on request). Further, as mentioned earlier, 23 airports exceeded 20,000 hr of annual flight delay in 1991. The average cost to airlines of these delays, at $1,600/hr, was $32 million for each airport.

Current FAA plans to address surface traffic levels of the present and future are contained in the Airport Surface Traffic Automation (ASTA) program, which includes the use of DGPS but is also based on a new primary radar for ground surveillance, ASDE-3, and the automation of radar returns through a software system known as the airport movement safety system (*5,* p. 5-2). Originally contracted in 1985, ASDE-3 has been delayed by a series of software and hardware development problems.

Use of DGPS and ADS alone for management of airport surface traffic was successfully demonstrated at Daytona Beach by three aircraft as part of the ASTA program (*3,* p. 55). The pure DGPS-ADS approach offers potentially better accuracy, is far less expensive, and offers compatibility with DGPS-ADS-based en route and approach technology. ASDE-3 systems are being implemented, however, to replace the ASDE-2 systems installed in the 1960s. The first 40 ASDE-3 systems are being commissioned. Thirty-five more are planned by September 1995. ASDE-3 installations cost approximately $4.5 million each (*11,* p. 41). FAA acknowledges that ASDE-3 will not be available at all airports because of cost considerations and that "it is important, therefore, to develop affordable sensors to provide a reliable surveillance source for terminal operations and to support automation development and airport capacity initiatives" (*5,* p. 5-13).

FUNDING CONSIDERATIONS

Airline

United Airlines has estimated annual operating losses related to ATC delays, system capacity limits, weather problems, cancellations, and a number of other flight inefficiencies variously at $500 million (*12,* p. 43), $630 million (*10,* p. 47), and $647 million (*3,* p. 53). On the basis of United's share of total ATA-member domestic departures, the $647 million United loss can be extended to a value of $6.2 billion annually for all ATA-member airlines, an amount that can be substantially reduced by GPS navigation, in combination with ADS and EVS technologies.

Foreign operators are experiencing losses from a variety of similar ATS problems. Lufthansa reported in 1990 that 17 percent of delays were related to ATC start-up operations, 19 percent of delays occurred in airborne operations, and the total cost of delays for the year was $92 million (*13,* p. 11). Air France reported an annual cost from congestion of $70 million (*13,* p. 11). Other estimates have suggested that GPS alone can save airlines $5 billion annually in fuel and other costs (*12,* p. 36).

Autoland operations based on GPS position data are independent of ILS signals but still require the presence of other landside Category III infrastructure elements. As mentioned earlier, successful autolands have been demonstrated to Category IIIB standards. Still to be resolved are integrity, continuity, and availability of the signals, and possible added accuracy requirements that may be imposed by FAA.

Public Sector

The contribution of the air transport industry to total world output was estimated in 1989 at some $700 billion. Air traffic system inefficiencies have a significant effect on the domestic and world economies.

Table 5 gives a conservative estimate of some annual public-sector costs associated with support of various ground systems used today for domestic navigation and surveillance of aviation operations. The data include labor (estimated at 40 percent), rents, utilities, spare parts, and flight inspections. Runway costs, such as lighting, are not included.

Decommissioning of the ground systems indicated in Table 5 would save, then, conservatively, $0.25 billion annually in public-sector costs. Decommissioning is feasible with the implementation of GPS and ADS.

By comparison, the infrastructure needed to support domestic GPS en route navigation consists principally of 20 to 30 DGPS ground monitor stations (30 to support Category I approaches throughout the United States) (*14,* p. 46), which might be estimated to cost between $100,000 and $200,000 each. Support costs will be a small fraction of those for older systems. To support ADS surveillance, a small number of additional ADS Mode-S communications ground stations may also be required. Software and hardware upgrades to ATC display and computer systems to accommodate GPS and ADS should be available within current ATC budgets, in such planned resources as the AAS.

CONCLUSION AND RECOMMENDATIONS

The air traffic system again suffers from overcrowding and undercapacity; upgrading the air navigation system will provide substantial relief. The best technical approach and the most cost-effective solution appear to be the same, essentially calling for relocating navigational resources from the ground to the airplane. To do so burdens airlines with an impractical investment requirement.

It appears equitable and appropriate that some form of public funding be applied to airline acquisition of the most cost-prohibitive and effective elements of the new technology, such as

TABLE 5 Estimated Annual Support Costs Associated with Navigation and Surveillance Ground Equipment, 1992[1]

System	Units in Service	Average Unit Cost	Total Annual System Cost
VOR/DME	1,039[2]	$86,000	$89,354,000
ILS	1,159[3]	81,000	93,879,000
NDB	1,575[4]	13,000	20,475,000
Surveillance Radar	--	--	50,000,000
TOTAL			$253,000,000

[1]Interview by author with Mark Kipperman, Science Applications International Corporation, January 17, 1994, Washington, D.C.
[2]1,039 total *(5)*, 950 operated by FAA *(5)*.
[3]1,159 total *(5)*.
[4]1,575 total, 728 operated by FAA *(5)*.

the enhanced vision system, to bring the benefits associated with it to airlines and the public. In addition, the investment made by airlines in older-technology airplanes, which is continuing, will be better preserved by retrofit of the new technology. Extending the useful life of those airplanes will benefit traditional airlines, low-cost start-up carriers, and the traveling public.

On the basis of indicators described in this research, it appears that by developing and implementing GPS for en route navigation and approach/landing, operations, complemented in both cases with ADS and EVS, we might expect the following:

- A reduction of 28 million mi flown in domestic operations by ATA-member airlines (increasing system capacity);
- Annual savings of $10 billion for the domestic economy;
- Elimination of more than $250 million annually for support of existing navigation ground facilities;
- Reduction of a $32 million annual cost generated by delay problem airports;
- Elimination of a $4.5 million per installation cost for ASDE-3 radar systems;
- Reduction of the $7.7 billion currently planned for airport infrastructure improvements; and
- Airline savings that are estimated at between $300 million and $500 million annually, for major carriers.

The price for avionics (1995 dollars) to equip an air carrier airplane with GPS, ADS, and EVS capable of the operations described in this paper, could approach $1 million per aircraft (interview with G. K. Knoernschild, Rockwell International, March 22, 1994). On December 31, 1993, there were 4,596 turbojet air carrier airplanes in the United States (*15*) and 2,208 airplanes operated by regional airlines in passenger service in the United States (interview with W. Coleman, Regional Airline Association, July 26, 1994).

To fit all the 6,804 airplanes with full-capability systems would require a total investment of $6.8 billion. [A substantially smaller number of retrofits can be expected, however, due to differences in equipage (e.g., FMS, autoland) and aircraft age, in some cases.] As mentioned earlier, for example, a runway upgrade program (such as that described for St. Louis) results in added accessibility by only a relatively small number of sophisticated aircraft. The promise of EVS would make St. Louis accessible to all equipped aircraft. In the absence of some form of public funding, the benefits of EVS, as currently envisioned, will probably not be realized at all.

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