A PROCESS FOR ESTIMATING COST/BENEFITS OF FUTURE AIR TRANSPORTATION SYSTEM OPERATIONAL CONCEPTS BASED ON 4D NAVIGATION

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Abstract

The aviation community worldwide has been working for sometime to define a vision of the future air transportation system. The overall progress thus far has been primarily at a conceptual stage. This paper integrates a number of operational concepts into a realizable vision for the National Airspace System (NAS). A process is defined to help develop future operational scenarios based on the makeup of year 2020 fleet mix and aircraft avionics capabilities, considering non-scheduled on-demand, charter, travel club, fractional and short-haul intra-city operations. A majority of aircraft are projected to be able to fly via 4D navigation and to assume a larger share of the responsibility for maintaining separation. This would require significant investment in avionics and the automation of the ground system and infrastructure. Cost/benefits analysis is a key portion of the process. Example results are presented to illustrate return on investment over time as more and more aircraft are equipped with enhanced avionics. The operational benefits of 4D navigation operations are derived from reduced air and ground delays determined from the NAS-wide simulation of future operations. The example presented compared the life cycle costs of air/ground enhancements as function of aircraft equipage to ascertain that the overall benefits outweigh the implementation costs over time. The process is based on a number of operational assumptions and likely air/ground system enhancements beyond the currently planned enhancements over next 10 years. The evaluation process presented in the paper can be used to help understand the benefits and limitations of the future operational concepts, and intends to help define an ideal, but realistic vision of the future air transportation system for guiding research cost effectively.

Introduction

The aviation industry is currently going through restructuring in response to economic sluggishness and new breeds of competitors. Concurrent with this process, technology and market forces are in play that will lead to a new breed of aircraft operators, open new markets, and offer service to more airports in order to meet future passenger and cargo demands. As passenger seats tend to become commodities, the airlines will seek to distinguish themselves through information technology leading to virtual and dynamic alliances with on-demand operators serving specific market niches with smaller and specialized aircraft. Air traffic service providers must also be prepared to respond to these aviation industry trends as they lead to diverse needs of the user population, significant increase in unscheduled demand, and management of complex traffic flows comprising new categories of aircraft such as Uninhabited Air Vehicles (UAV) and Vertical Short Takeoff and Landing (VSTOL) aircraft serving intra-city airports and business centers.

A number of ideas are presented in the literature to define concepts for future NAS operations [1-11]. The most concise vision and concept of operations for a future globally harmonized National Airspace System are documented by the RTCA [12]. These are based on the philosophy that all users operate in the NAS without constraints and the user requirements drive global aviation. Before pursuing any revolutionary concepts, it is important to understand the need for a change towards certain goals, and whether the change will be cost effective.

This paper presents an approach for modeling the future air transportation system for the year 2020 and beyond, and defines a process for comparing costs with potential operational benefits of the concepts based on a new Communication, Navigation, Surveillance (CNS) and Air Traffic Management (ATM) system paradigm. The key aspects of the new paradigm used to define future operational concepts are: 1) gate-to-gate problem-free flight planning independent of lookahead times based on aircraft self-delivery within defined time tolerances using 4D navigation; and 2) increased delegation to the aircraft of responsibility for maintaining separation including using sense and avoid capabilities to support visual-like separations of today.

The Impact Assessment Process

The overall objective of the future operational concepts is to enhance NAS safety, efficiency, flexibility, capacity, and security. By setting specific performance goals to alleviate constraints in the current system, realistic and achievable targets are established that allow the aviation community to check its progress and make adjustments where necessary. It is also important to define metrics for comparing the pros and cons of various ideas being discussed by the aviation community, and select the ones that lead towards the target goals cost effectively. Figure 1 shows an eight-step process for impact assessment of selected future operational concepts. To demonstrate the application of the process, an example is presented involving the gradual implementation of 4D navigation and increased delegation of separation responsibility. The following is a description of the steps involved in the process:

Step 1: Define operational concepts to be explored for the assessment of impact on the NAS.

Step 2: Determine traffic demand and type of aircraft and aerospace vehicles that are expected to operate in the selected time frame.

Step 3: Set future NAS performance goals for the selected time period.

Step 4: Based on the selected concepts and corresponding operating procedures, define scenarios for modeling the future environment.

Step 5: Develop a NAS-wide simulation model to postulate future baseline operational scenarios for relative comparison with different operational

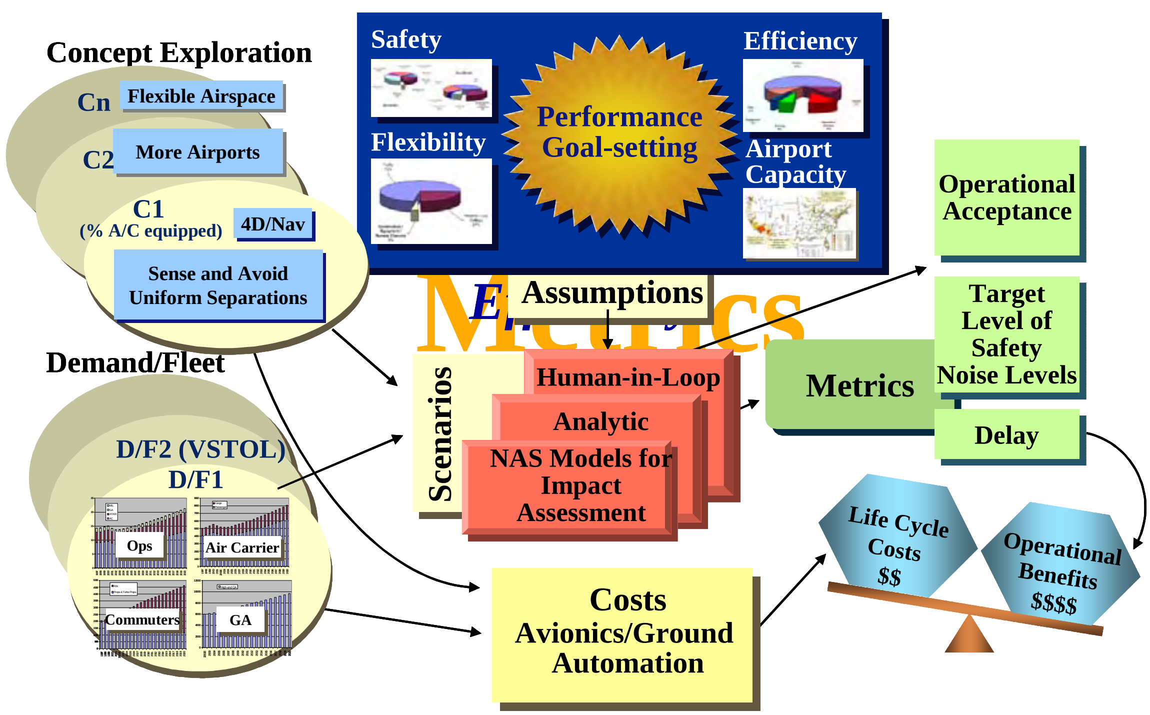


Figure 1: Performance Goal setting and Impact Assessment Process

concepts considering air/ground system enhancements.

Step 6: Define operational assumptions based on the consideration of future air/ground technologies mitigating some of the causal factors affecting NAS performance.

Step 7: Generate comparative system performance metrics such as overall gate to gate system delays and level of safety.

Step 8: Perform cost/benefit analysis to determine if the operational benefits will outweigh the air/ground implementation costs.

Efficiency metrics based on reduction in flight delays will help determine operational benefits in terms of reduction in user direct operating costs. These benefits will not be achieved without an investment in avionics and ground-based automation. However, the cost/benefit assessment example presented later in the paper provides some insight on a relative basis to identify areas for cost effective investment.

Example Definition of Operational Concepts: Aircraft Self-Delivery and Increased Delegation of Separation Responsibility [13]

By the year 2020, a significant majority of aircraft are envisioned to be capable of flying 4D navigation. A 4D flight plan contains a trajectory that includes waypoints specified by latitude, longitude, altitude, and the desired time of arrival at each waypoint with a specified time tolerance at which the flight will arrive. These flights will have a problem-free trajectory to avoid weather or traffic congestion that is projected to occur along the way when the flight planning process was done. Each trajectory represents a contract, where the flight will, barring unforeseen events, self-deliver at the waypoints and meet the scheduled arrival time at the destination airport within the specified time tolerances using onboard speed adjustments.

Once the aircraft is assured of staying within the specified time window, the resulting translation into a longitudinal distance could help establish the length of a protection volume of airspace at each waypoint. The lateral dimension is defined by the Required Navigation Performance (RNP) and the vertical dimension is based on an altitude deviation of +/- 250 ft. Based on the aircraft performance within the volume 99 percent of the time, the prediction of the protection volume becomes independent of lookahead time.

Enhanced avionics will also enable aircraft to assume a larger share of the responsibility for maintaining separation by enabling aircraft to sense and avoid traffic permitting operations such as “see and be seen” in current Visual Meteorological Conditions (VMC). These capabilities may also lead to reduced separation standards.

It is envisioned that the aircraft will gradually equip with these advanced avionics capabilities and the future NAS will have to manage aircraft with diverse capabilities. Figure 2 illustrates some of these concepts as they relate to the operations of different types of flights. Some of the users will file a flight plan with a 4D trajectory that will be free of any problems with weather or traffic congestion. However, as the situation changes while the aircraft are airborne, the flight may dynamically re-plan to deal with the changes. The flight may have constraints imposed, such as an adjustment to the scheduled time of arrival at a waypoint, to solve the problems. These resolutions are coordinated between the flight and the ATM system, and the flight will meet the constraints by following its revised flight plan.

Unequipped or non-4D aircraft will file flight plans as today. These flights will specify their intent in terms of routing and altitude but not times (time tolerances) at waypoints. As discussed earlier, the separation responsibility will depend upon the type of operations: for non-4D flights the controller is responsible for separation, while for 4D flights various levels of responsibility for separation may be delegated to the pilot depending upon several factors such as the geometry of the flight paths and aircraft speeds.

Segregation of some segments of airspace is envisioned where different operations or a mix of aircraft performance occur in an otherwise complex or congested area. For example, VSTOL operations into and out of major airports could use dedicated corridors to help reduce the complexity and maintain safety during such operations.

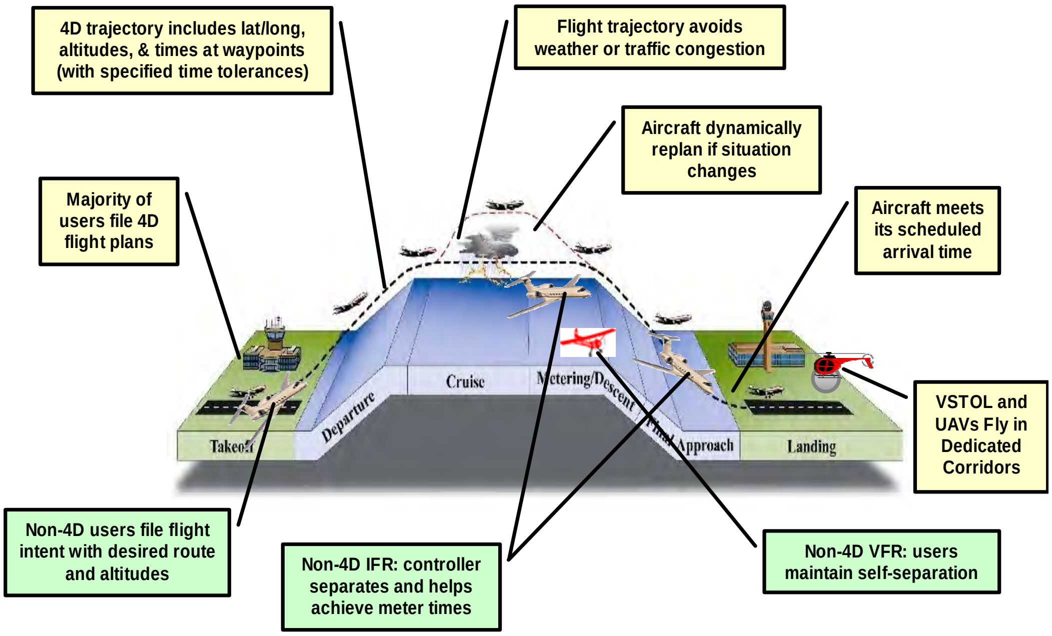


Figure 2. Mixed Equipage Flight Operations

Future Traffic Demand and Aircraft Fleet Projections [14]

For this example, the focus was on the year 2020 and on 30 of the largest airports. Figure 3 shows the projected number of annual operations at 30 major airports until the year 2020. The recent FAA Terminal Area Forecast [15] data were used to generate demand for the years 1997 to 2020. The year 2014 rate was used and assumed constant for demand predictions from the year 2015 to 2020. These forecasts reflect short-term reduction in demand after 11 September 2001 and strong recovery for certain segments of the demand including high-end General Aviation (GA) aircraft. Figure 4 shows the projected number of Air Carrier (AC) and cargo aircraft operating at the 30 major airports. These projections were derived using the unique aircraft tail numbers observed in the Airlines Service Quality Performance (ASQP) data for October 2002, as a baseline. The projected growth over the next 18 years used the FAA Aerospace Forecasts until the year 2014[16]. The 2014 growth rate of 2.9 percent was used and assumed constant for the years beyond 2015. The projections include aircraft retirements and new acquisitions of narrow-body and wide-body jets. Figures 5 and 6 highlight the corresponding growth in the number of commuter and GA aircraft, predominantly high-end GA, respectively operating at the above airports. Note the large projected increase in the number of Regional Jets (RJs).

Future Operational Scenarios

Some of the aircraft equipped with Flight Management Systems (FMS) have a Required Time of Arrival (RTA) capability to enable the aircraft to arrive at a specified point in airspace at a desired time. For 4D flight trajectories, the aircraft are expected to stay on a pre-established 3D profile, and meet the desired times at waypoints by only speed adjustments needed to compensate for variances between predicted and actual winds. The challenge lies in determining the desired waypoint times in a mixed 4D/non-4D aircraft operational environment, so that the 4D flight planning uncertainties are minimal. As a result, 4D flights should be able to fly from lift off to touchdown with negligible delays most of the time. However, regardless of the sophistication of future avionics and ground automation systems, traffic congestion at times due to airport constraints and convective weather will require flights to deviate from the original plans, resulting in unavoidable delays.

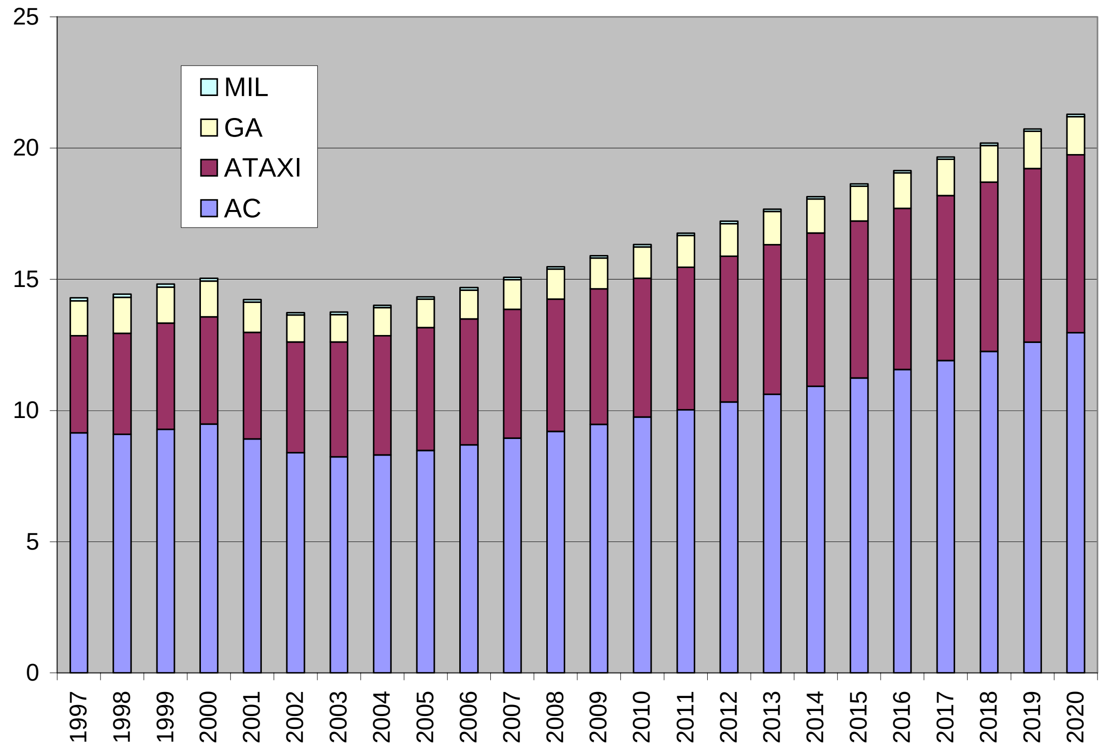


Figure 3. Projected Operations by Service Provisions at 30 Major Airports in Future (in millions)

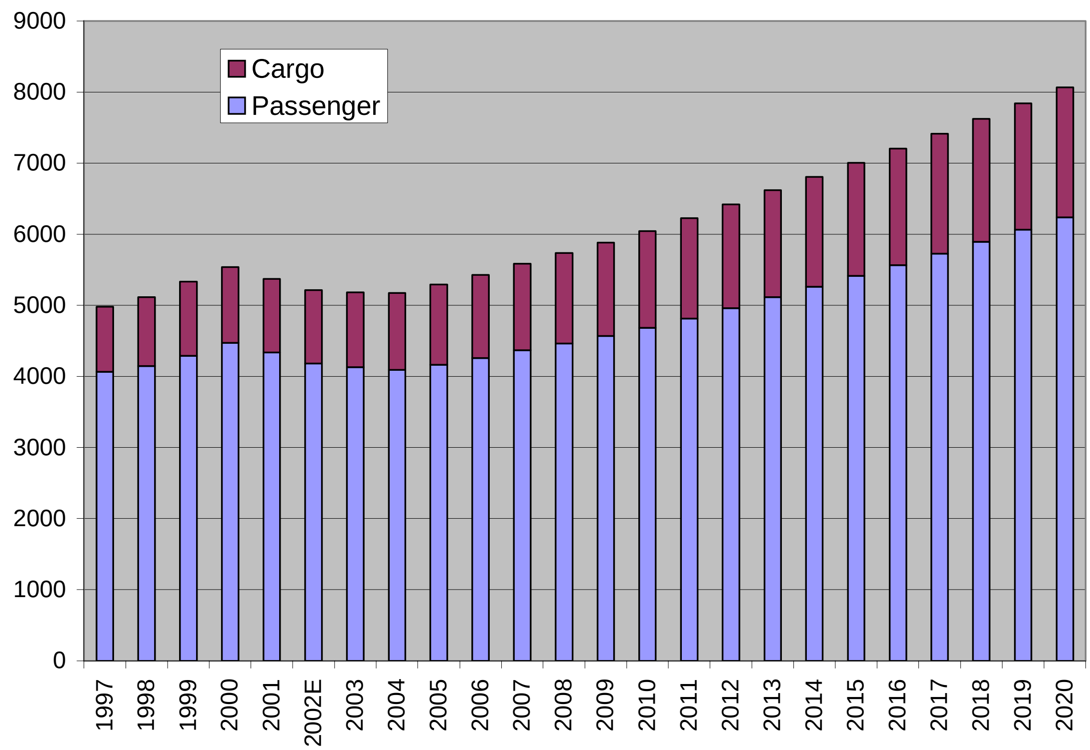


Figure 4. Projected Number of Air Carrier and Cargo Aircraft Using 30 Major Airports in Future

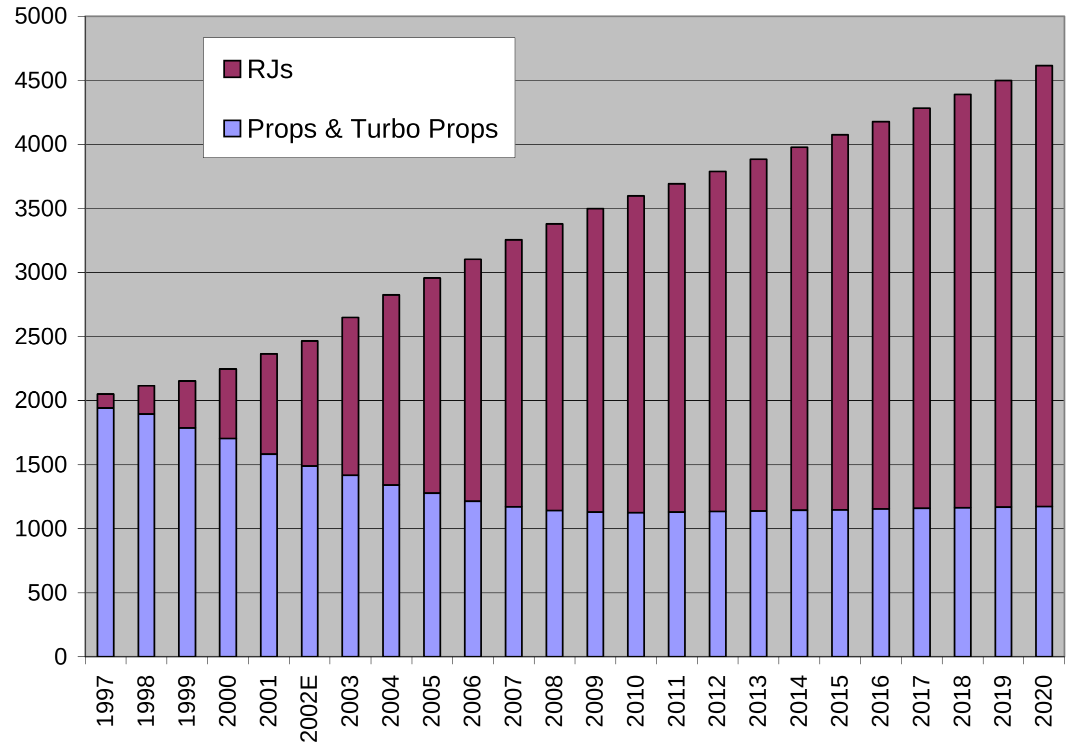


Figure 5. Projected Number of Commuter Aircraft Using 30 Major Airports in Future

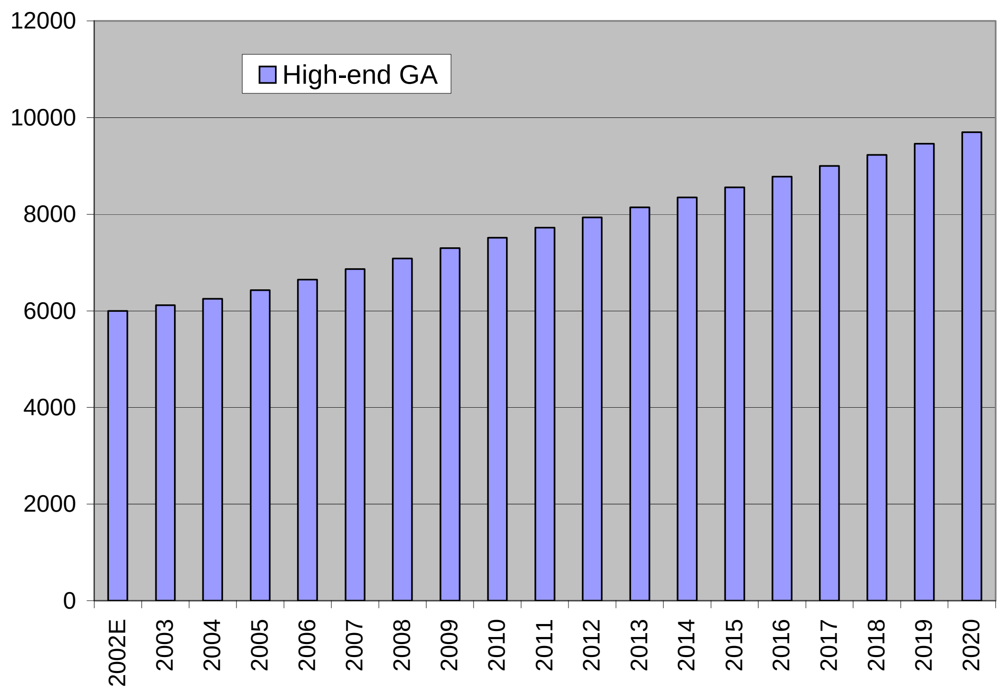


Figure 6: Projected Number of High-end GA Aircraft Using 30 Major Airports in Future

In the simulating of future operations for the study example in this paper, a baseline scenario was defined considering traffic for year 2020 as discussed earlier without aircraft flying 4D navigation or being delegated increased levels of separation responsibility. The airspace sector capacities are maintained at today's levels, while the capacities of the major 30 airports are increased based on planned new runways and other improvements. A number of scenarios are then developed by introducing equipped flights in various percentages – ultimately all NAS operations are 4D equipped and able to assume increased separation responsibility.

Operational Performance Assessment Using a NAS-Wide Model

MITRE has developed a NAS-wide simulation model whose main purpose is to assess the system-wide effect of changes to the NAS and the global air traffic management environment. The model combines explicit trajectory modeling with delay computations provided by traditional methods such as queuing models. These advances allow airspace and airports to be modeled to incorporate procedures to enhance airspace and airport capacities, including such factors as miles-in-trail restrictions, ground delay programs, complexity estimation of sectors, and conflict counts.

The model has been applied to address many research questions both within the NAS and Europe such as: 1) evaluating different traffic flow management strategies for handling excessive volume related to runway outages at Newark International airport (EWR); 2) computing the system-wide effect of an airline scheduling practice known as "de-peaking."; and 3) estimating the benefits of investing in advanced avionics for one large carrier's European flights. The model can be used to analyze NAS impacts of local changes, and has the fidelity to assess trade-offs among en route and terminal area operational modifications.

The model uses mixed discrete-event and continuous-time simulation techniques to advance it beyond the purely discrete-event aviation models of the past. The advanced techniques allow it to compute flight trajectories using a variety of different methods simultaneously within the model. It is capable of simulating 70,000 flights in about twenty minutes when less detailed trajectories are required, or in less than two hours using significantly more detailed flight trajectories.

Using some advanced animation algorithms that directly drive graphics processors inside a Windows®-based PC, the model can display selected metrics as an animation of flights. A screen snapshot of this capability is shown in Figure 7. This allows analysts and users to view and compare statistical metrics in real time as the simulation is replayed, enhancing understanding and assisting in gaining user acceptance of the model.

This model is ideally suited for use in the impact assessment process and was used for the example being presented in this paper.

Operational Assumptions for 4D/Non-4D Flight Operations

The following assumptions were used to develop inputs to the NAS-wide model defining future airspace and airport capacities to measure gate to gate delays for all flights in 2020 NAS operations.

4D flights:

- En route airspace sector capacity limit: no limit
- Terminal airspace capacity limit: no limit
- Major airport departure/arrival capacity: VMC
- All other airports: no limit
- Departure/arrival in-trail separations between 4D/4D and 4D/Non-4D aircraft: VMC

Non-4D flights:

- En route airspace sector capacity limit: based on Monitor Alert Parameter (MAP)
- Terminal airspace capacity limit: based on historical Maximum Instantaneous Airborne Count (MIAC)
- Major airport departure/arrival capacity: VMC or Instrument Meteorological Conditions (IMC) depending upon airport weather conditions
- All other airports: no limit

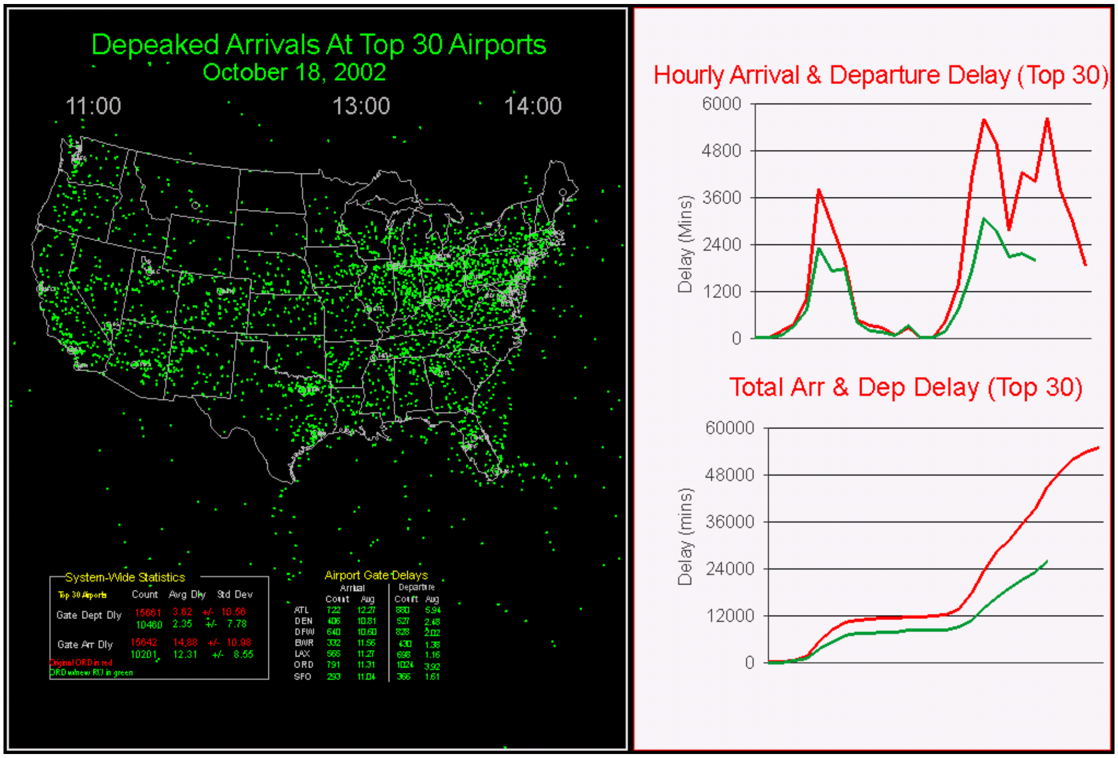


Figure 7: NAS-Wide Model Output Information Displays

- Departure/arrival in-trail separations between Non-4D/and other aircraft: VMC or IMC depending upon airport weather conditions

Convective weather: affects all flights

- NAS wide coverage: average 5 percent (See Figure 8)
- En route airspace capacity limit: 85 percent of MAP

These represent an initial set of assumptions and will be refined during future analyses.

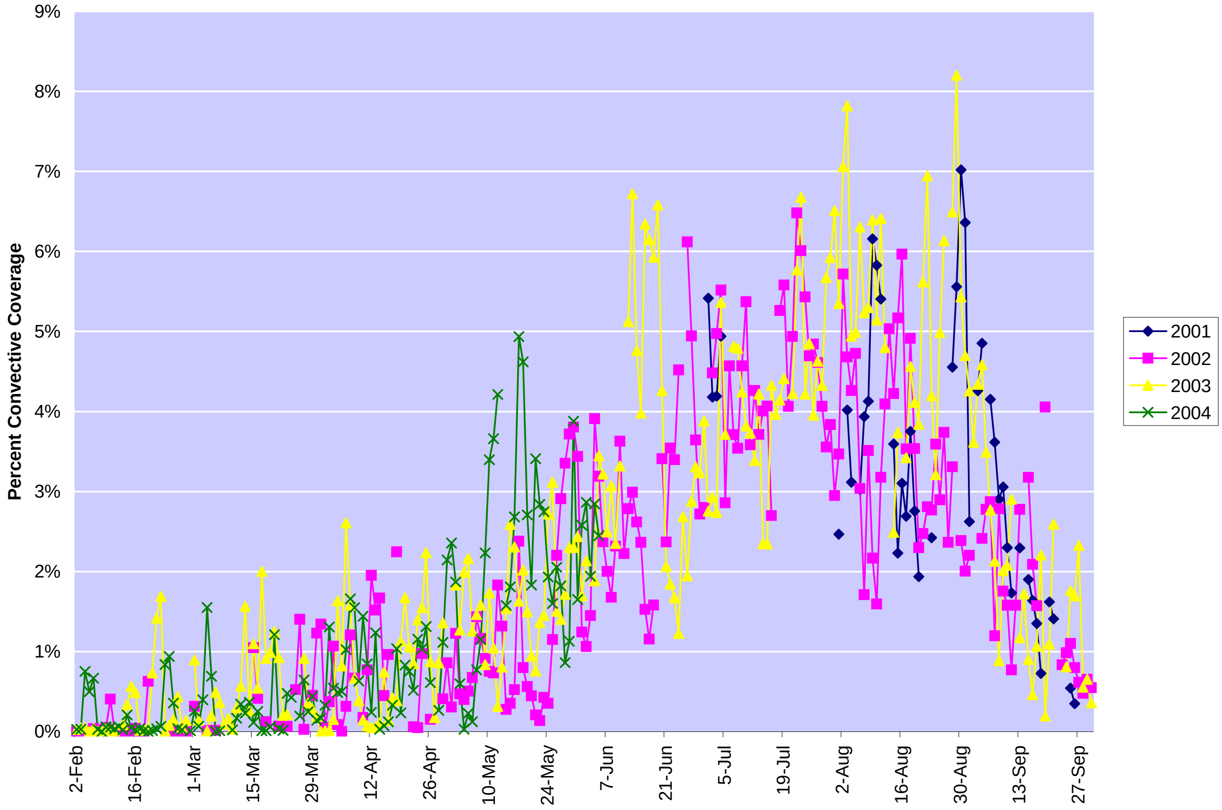
Performance Metrics

The simulated scenarios used in this example represent year 2020 operations with various percentages of aircraft equipped with advanced navigation and other avionics capabilities. Based on the assumptions discussed above, the model simulated airport and sector capacities The model logic was updated to determine minimum flying times between city pairs as desired by users to measure flight delays. Average gate to gate delay per flight was determined for the 2020 baseline scenario (representing no advanced equipage). Then average flight delays were also obtained from simulation runs for operations including 10, 30, 50, 70, 90 and 100 percent advanced equipages. The average flight delay as a function of aircraft equipage is shown in Figure 9.

In the future, additional modeling and simulation capabilities (including human-in-the loop) are needed for a complete impact assessment in terms of a broader set of metrics, such as noise footprints, target level of safety and operational acceptance for identifying the best features of the future vision of NAS.

Cost/Benefits Analysis Results

Figure 10 shows the overall cost/benefits determination process. The estimates for ground costs in this study include implementation costs for CDM, LAAS, ADS-B and NEXCOM with TMA updates to support specific percentage of 4D aircraft [17]. The estimate of these costs was US $2.95 billion.



Source: NOAA/FSL National Convective Weather Database

Figure 8: Percent Convective Coverage in NAS by Day

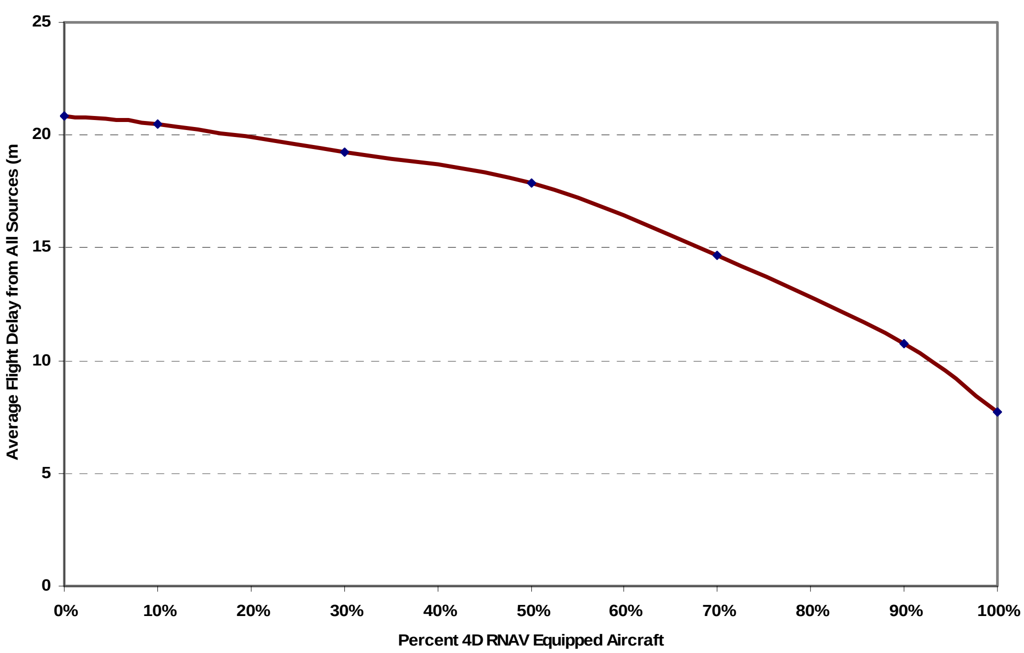


Figure 9: Average Flight Delay for Year 2020 Operations for Advanced Equipage Levels

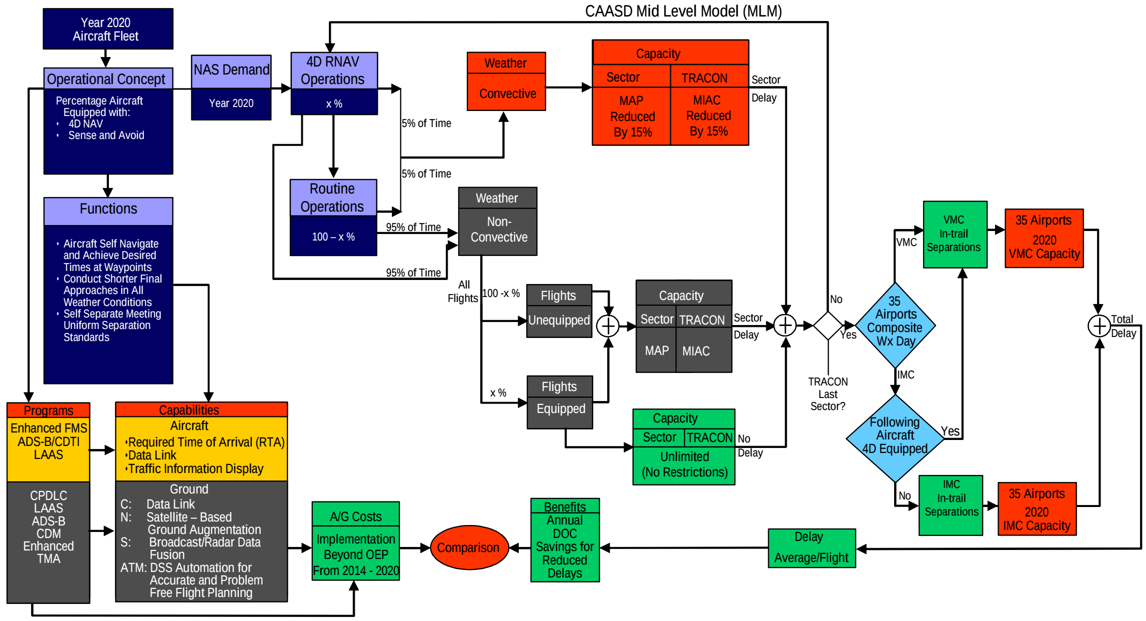


Figure 10: Overall Cost/Benefits Determination Process

The avionics costs are based on estimated costs of CPDLC, ADS-B/CDTI and LAAS for different categories of aircraft such as air carrier, commuters and high-end GA. The number of these aircraft operating today is determined from current tail numbers and projected for the future using FAA forecasts. The costs for equipping the fleet with specific advanced avionics to support 4D operations and increased delegation of separation in 2020 are shown in Table 1 in year 2003 dollars. The benefits for these operations were determined based on savings in direct operating costs resulting from airborne delay reduction for the equipped aircraft in each category. Benefits from reduced ground delays and passenger value of time were not considered.

Implementing 4D navigation equipment and procedures is expensive. Equipping aircraft that can navigate required 4D operations would involve significant investment of advanced avionics. In addition to costs improving operations in the air, there are costs for ground improvement including that of implementing needed procedures. Our preliminary cost estimates indicate that the total costs may vary between US \$3.4 to \$7.8 billion, depending on percentage of equipage.

Figure 11 demonstrates the initial cost estimates with regard to different percentages of equipage. As evident, there is a significant initial cost in implementing these advanced capabilities. Even when only 10% of the total aircraft equip, the present (in 2003 dollars) value of the total cost is around US \$3.4 billion. The cost increases at a diminishing rate with respect to different levels of equipage, i.e., initial rates are higher than the subsequent ones. If all aircraft have been equipped with advanced avionics capabilities, the total cost is estimated to stand around US \$ 7.8 billion. Relationship between cost and equipage rate suggests an underlying generalized cost equation as follows: Cost = A*(equipage rate)$^{\alpha}$ where A is a constant and α is the intensity of adoption. Experimentation with data parameterizes the relationship as follows: Cost = (3.3953)* (equipage rate) 0.481. In other words, for every 1% increase in equipage rate, cost will increase at a diminishing rate of 0.48%. This estimated equation explains cost for 99.8%.

Calculating benefit is always a tricky task, particularly in situations when both beneficiaries and the extent and magnitude of a future investment are unknown and quite complex. In order to simplify those complexities, we assume that benefits accrued from implementing these advanced capabilities take the form of reduction of delays. Estimates of the average delays for various

Table 1: Estimated Avionics Costs for 2020 Fleet

	Air Carrier (8,068 in 2020)		**Regional Jets** (3,439 in 2020)		**Turboprops** (1,174 in 2020)		**High-End GA** (9,697 in 2020)	
	Cost per aircraft ($k)	Fleet Cost ($M)	Cost per aircraft ($k)	Fleet Cost ($M)	Cost per aircraft ($k)	Fleet Cost ($M)	Cost per aircraft ($k)	Fleet Cost ($M)
Controller Pilot Data Link Communications (CPDLC)	30	242	20	69	20	23	20	194
ADS-B with Cockpit Display of Traffic Information (CDTI)	185	1,493	70	241	70	82	70	679
Local Area Augmentation System (LAAS)	88	710	78	268	78	92	78	756
TOTAL	303	2,445	168	578	168	197	168	1,629

- All costs in 2003 dollars.
- Aircraft forecasts use FAA projections through 2014 with continued growth at the 2014 rate.
- Assumes that current aircraft are retired at 25 years of age.

scenarios were obtained by runs with the NAS-wide model and were previously shown in Figure 9. In other words, we estimate the present value of benefit by calculating the amount of delays saved by implementing the capabilities. The total (initial) estimated benefit by this measure ranges from US $0.36 billions to US $ 12.6 billions with respect to 10% and 100% equipage, respectively as shown in Figure 12. It is assumed that the benefits are realized over a 15-year period.

Notice that while cost increases at a smaller rate vs. increased levels of equipage, estimated benefits increase at a significantly higher rate [see Figure 12]. Contrary to cost estimates, benefits do not materialize fast unless more aircraft have been equipped with the advanced avionics capabilities. Hence, total present value of benefit is only US $0.36 billions corresponding to 10% equipage rate. However, the model results show that the benefit increases at a faster rate particularly after the equipage rate has reached the critical mass above 50%. At the 100% levels of equipage, total present value of benefit has been estimated to be US $ 12.6 billion.

The underlying equation that best captures the benefit representation is as follows: Benefit = $B*e^{\beta(\text{equipage rate})}$ where B is a constant and e is the base of the natural log (=2.718282). Fitting this equation to the underlying data returns the estimated values as follows (with an R^2=97.3%): Benefit = $0.1389*e^{0.7885(\text{equipage rate})}$.

Given these cost and benefit equations and estimates, it is important to know at what levels of equipage, then, will this investment makes sense? More specifically, at what level of equipage will the cost be equal to benefit given cost, benefit, and their implementation schedules, equipage levels and their impact on benefit, and other factors (e.g., rate of inflation, and discounting factors) determining the opportunity cost of capital? Alternatively, one can seek to find the number of years that may make this investment feasible assuming a certain level of equipage, and hence, cost and benefit.

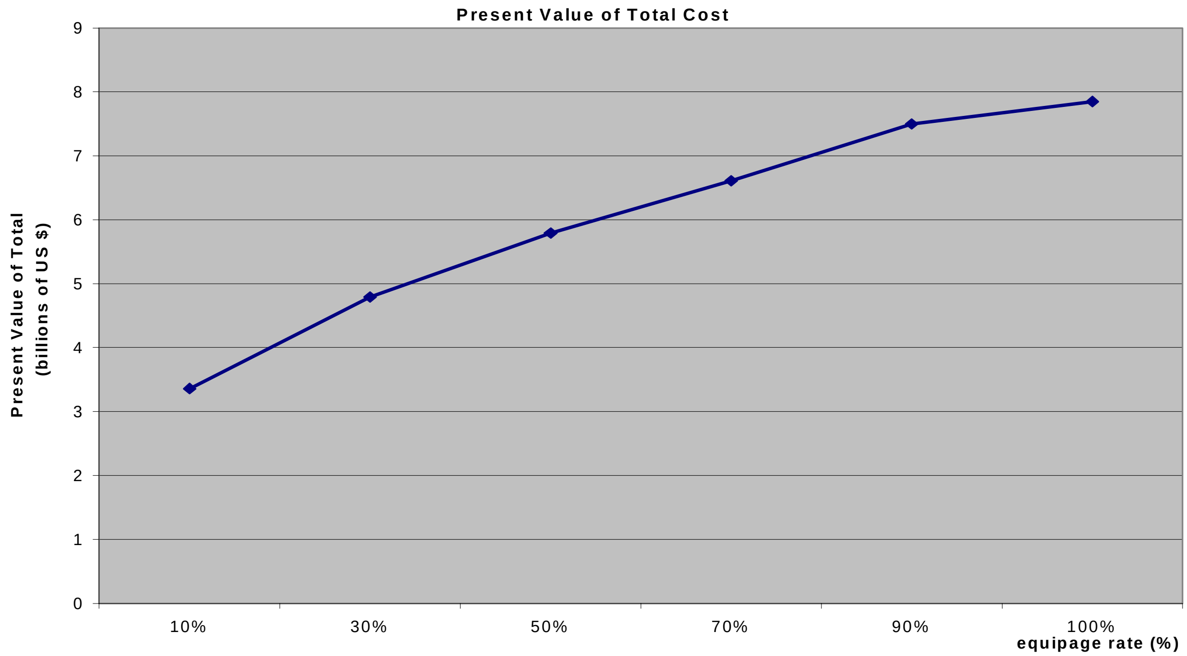


Figure 11: Present Value of Initial Cost Estimates

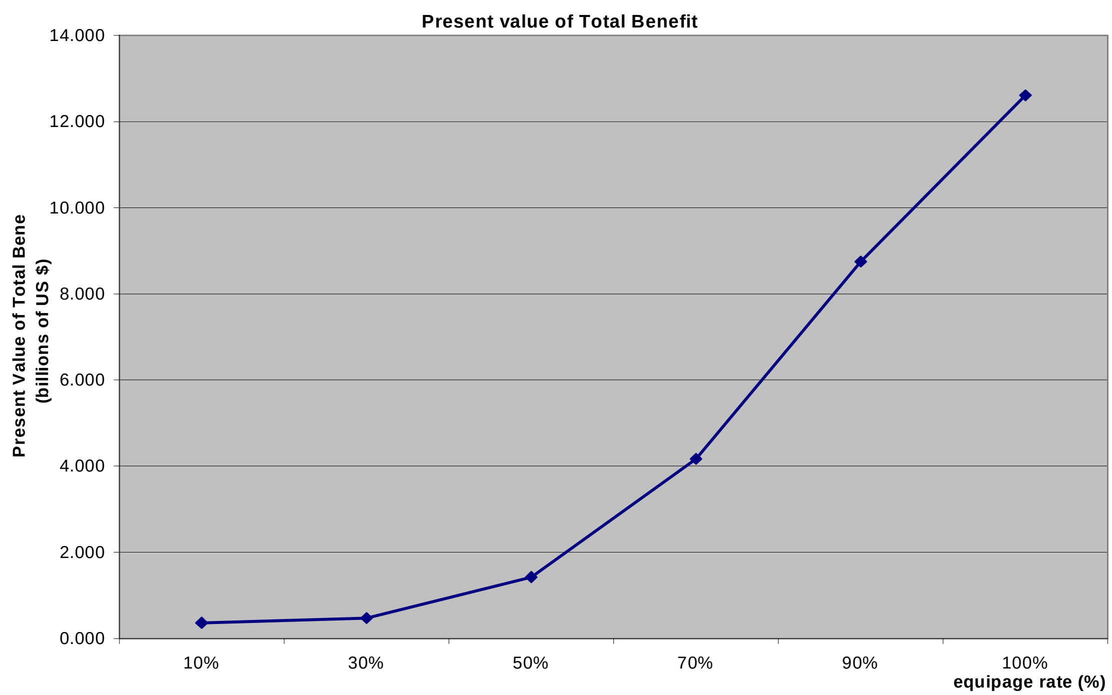
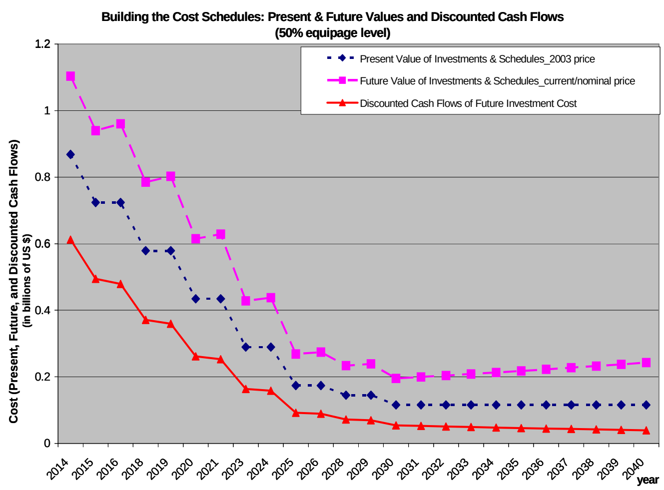


Figure 12: Present value of Total Benefits of 4D NAV Operations

In order to answer these questions for our illustrative example, we had to make certain assumptions regarding the implementation schedules, for costs and benefits for given equipage rates, rate of inflation and discounting rate. We assumed that investment promoting these advanced operations takes place over a period of 15 years, starting from 2014 and ending in 2031. The life cycle of the investment is assumed to be 24 years (2014-2040) with operations and maintenance costs exogenously set (2%) for the last 9 years (2032-2040).[1] In comparison, benefits are realized over a period of 15 years, 2014-2031. We assumed that the rate of inflation for this period will be 2.2% a year and a discount rate of 5.5% a year. Both these rates come from projections made by the Congressional Budget Office. Using this information, we can generate three sets of estimates for costs and benefits (i.e., present, future, and discounted flows) corresponding to different years assuming a certain level of equipage. Estimates at 50% equipage are shown in Figure 13.

Using the flexible forms of equations for both discounted costs and benefits, we can find the equilibrium solution, i.e., number of years where discounted cost = discounted benefit yielding Net Present Value (NPV) = 0. An example of this step for 70% equipage is shown in Figure 14.

The equilibrium point can be determined for each scenario – an example illustrating this step is shown in Figure 15. As illustrated in Figure 15, with 70% equipage, it was estimated to take 9 years for discounted flows of costs to be equal to discounted flows of benefit. Using this procedure, i.e., varying equipage level and finding equilibrium between discounted costs and benefit, we find that the lower the equipage level, the longer it takes for investments to become economically feasible. This relationship is captured by the year-equipage level trade-off in above figure. For example, given the assumed schedules for cost and benefits, inflation and discounting rates, equipage rates below 50% and/or more than 12 years of gestation period may not be economically feasible.



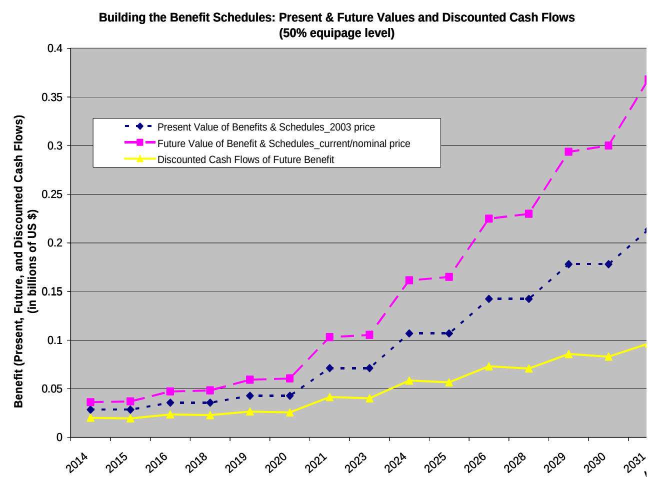


Figure 13: Present, Future and Discounted Flows of Costs and Benefits for 4D NAV Operations

[1] It is not necessary to have investment schedule set this way. As a matter of fact, any types of investment schedule will suffice. A schedule of implementation for both cost and benefit realization is nonetheless necessary for this analysis. Furthermore, we set the O&M cost fairly low (2%) in relation to total cost and make it exogenous. It is important to note, however, that O&M costs for many FAA programs are indeed exogenous and supported by mainstream budget.

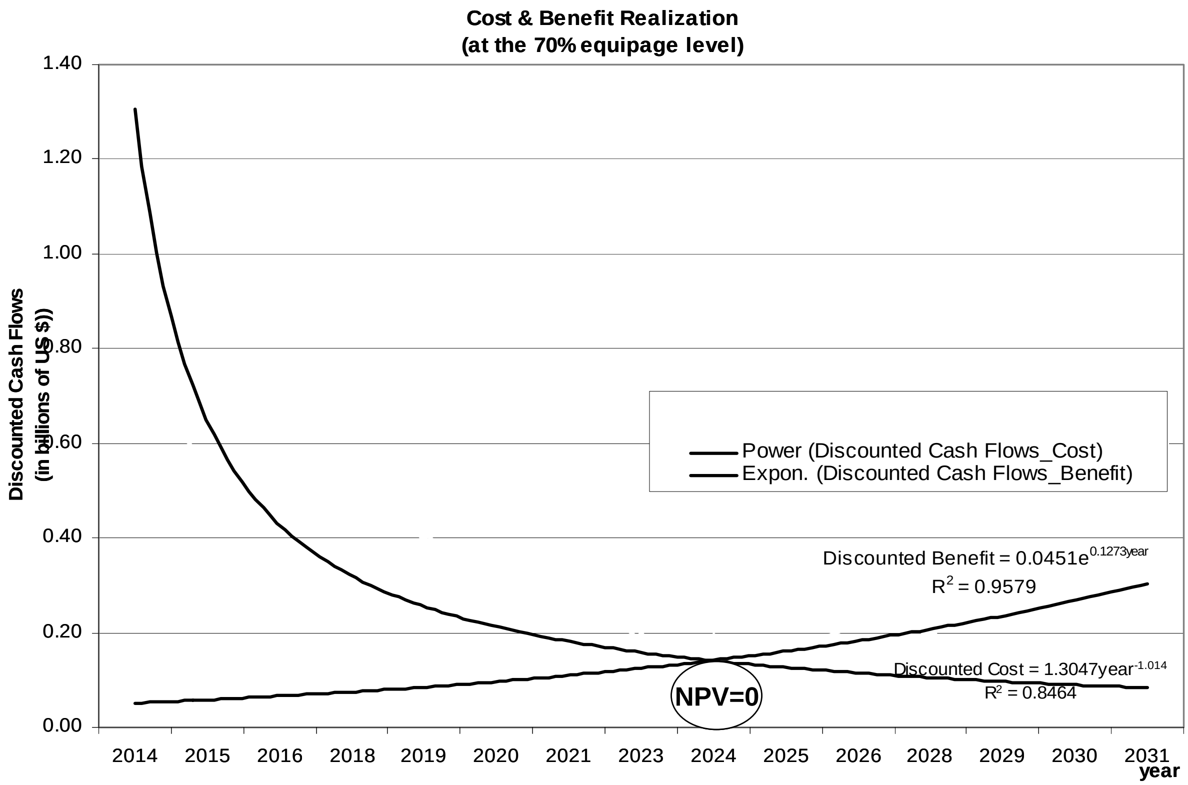


Figure 14: Equilibrium in Discounted Costs and Benefits for 4D NAV Operations

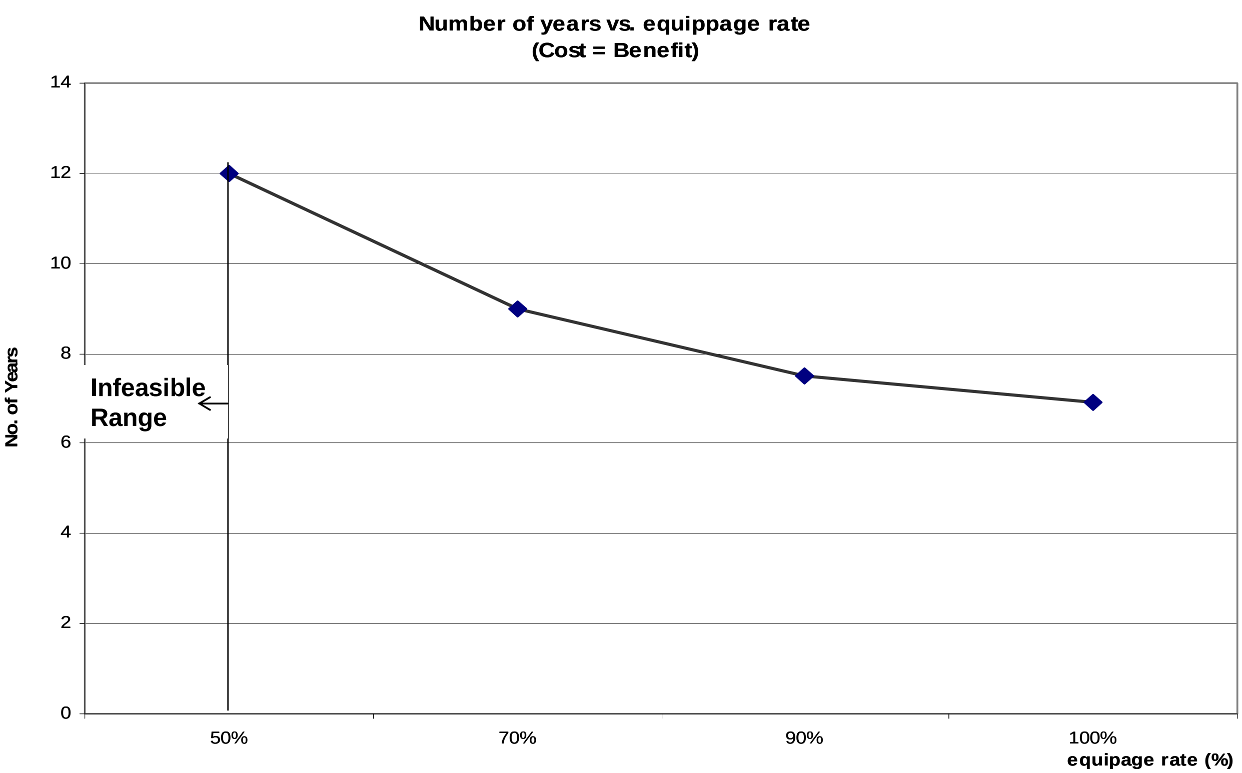


Figure 15: Trade-Off Between Number of Years and Equipage Rates

Summary

The introduction of new aircraft types with enhanced technologies and varying markets for air transportation pose a challenge for future air traffic services worldwide. Efforts are underway to develop new ideas and define revolutionary operational concepts to meet these challenges and establish a vision for the aviation industry in the 2020s. The development of these ideas is just the beginning, the real value lies in knowing the benefits to the aviation community and how they lead towards the desired goals. This paper presents a process to understand the merit of the diverse operational concepts when integrated into future NAS, before making commitments for further development. The paper presents an example by applying the process to the concepts of 4D navigation and increased delegation of separation maintenance to the aircraft to show the cost effectiveness of the these operations.

These estimated costs and benefits are based on a number of operational assumptions and likely air/ground system enhancement costs beyond the currently planned enhancements over next 10 years. Benefits for reduction in ground delays and passenger value of time will add to the overall benefits. However, these estimates are not an absolute assessment of costs and benefits for future concepts, but simply provide a basis for relative comparison with other concepts only. It is envisioned that the process presented will be applied often to help understand the pros and cons of various operational concepts for establishing a roadmap of future research and development.

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