# FAA Airport Design Competition for Universities
# Design Package Submission Form

Participating individuals or teams are required to submit the design package using this form. In additon, one hard copy of the full proposal plus the original of the Sign-off (See Appendix D in Design Submission Guidelines) form must be mailed to the Virginia Space Grant Consortium, 600 Butler Farm Road, Suite 2253, Hampton, VA 236666. All electronic and hard copy submissions must meet the 5 pm (Eastern Daylight Time) deadline on April 20, 2007. It is strongly recommended that a mail service that certifies delivery be used. All submissions will be acknowledged via email.

By proposal submission, Competition participants are agreeing that their proposal may be publicly shared. In addition, participants are giving permission that photographs that may be taken as part of Competition activities can be used for public information purposes and to promote the Program.

If you have questions regarding the Design Package submission process, you can contact the Virginia Space Grant Consortium between 8 a.m. and 4:30 p.m. EST on weekdays at 757/766-5210. Click here for Deraile_d Submjssion Guict lines.

**Full competition guidelines and all updates are posted on the Competition Website:**
http://www.faa.gov/runwaysafety/design_competition. him.

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|---|---|
| Institutions(s): | University of Virginia |
| Design Challenge Area: | Runway Safety/Runway Incursions |
| Specific Challenge Selected: | Runway Safety/Runway Incursions: Expanding situational awareness of pilots and ground operators on the airfield. |
| Level(s) of students(s) involved: | Both |
| Estimated number of participants: | 2 Undergraduate<br>3 Graduate<br>1 Faculty Advisors<br>1 Other, please describe: Graduate Advisor |

*Four components of the Design Package in PDF Format.*

Executive Summary

Main Body

Required Appendices

Optional Appendix

Approve/Reject:

. ) Approve Disqualify

*Reasons for Disqualifcation:*

[ **Submit** j

## I. Executive Summary

This paper proposes use of a systems engineering approach as the basis for implementing new operational system configurations to reduce the rate of serious runway incursions while ensuring that the introduction of new solutions does not inadvertently reduce safety compared to the levels achieved by the current ground traffic control system. Our proposal uses: I) statistical analysis, 2) data clustering analysis, and 3) economic analysis to determine an effective manner for implementing current and future ground traffic control system configurations.

Our statistical analysis shows that it would take multiple years of testing to assure that new traffic control system configurations improve the safety levels achieved by the current ground traffic control system. Therefore, we recommend that new system components should first be introduced as part of back up system configurations to augment the current ground traffic control system. We show that this approach would reduce the safety validation requirements, since they would only need to be shown as not adversely impacting the current ground traffic control system's normal performance while serving as a backup.

Our data cluster analysis shows that it is possible to quantitatively group airports so that we can extend testing results from one airport to other similar airports. While we do not claim that our parameter choices are optimal, we recommend that the FAA conduct a cluster analysis to significantly reduce testing requirements while assuring current safety standards.

The economic analysis indicates that the proposed solutions will not financially burden any one stakeholder group enough to prevent or delay implementation of a solution. The solution that faces the greatest impediment due to cost is ADS-B. Therefore, we recommend that the FAA carry out research to reduce the cost of ADS-B avionics and to consider ADS-B system configurations for ground traffic control that do not require all aircraft to be equipped.

# A Systems Approach to Runway Incursion Prevention

[1]

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## Table of contents

**II. Introduction and Background**

On the evening of June 9, 2005 at 19:39: IO pm Aer Lingus flight 132, carrying 260 crew and passengers, was cleared for takeoff at Boston Logan International Airport. Five seconds later, U.S. Airways flight 1170, with I 09 people onboard, received the same clearance from a second control tower located at the opposite end of the airport. As they applied power for the takeoff roll, neither of the pilots involved was aware that their clearances would lead them to a potential collision at the point where their respective runways intersected. Moments before the impending catastrophe, the U.S. Airways first officer became aware of the situation and alerted the flying pilot to take immediate evasive action. Later reports indicated that the two airplanes barely diverged by a distance of less than 200 feet [2].

The chilling circumstances of this event, categorized by the Federal Aviation Administration as a Type A runway incursion (RI), are by no means an anomaly. In the year 2006 alone, 313 separate runway incursions were reported in the United States, 27 of which [3] were classified as requiring "extreme action to narrowly avoid a collision" or exhibiting a "significant potential for collision". With the current volume of over 150,000 operations per day predicted to triple by the year 2025 [4], the risk of a major runway incursion resulting in the loss of life continues to grow.

As part of its ongoing efforts to reduce the severity and frequency of runway incursions [5], the FAA in partnership with NASA, has launched a series of research and development initiatives to investigate the broad spectrum of potential solutions. Ranging in complexity from relatively simple procedural changes and new painting schemes to the possible introduction of a Global Positioning System (GPS) datalink-based aircraft monitoring network (ADS-B), the proposed solutions take a variety of approaches in attempting to solve the issue of runway incursions [6]-[11]. Among these, the specific solution components that we have incorporated in our analysis include: Procedural Modifications, Enhanced Painting Schemes, Final Approach Runway Occupancy Signal (FAROS) Lights, Airport Surface Detection Equipment Model-X (ASDE-X) Ground Surveillance Radar, Runway Status Lights (RWSL), and Automatic Dependent Surveillance Broadcast (ADS-B). Figure I orders these solution components hierarchically by complexity.

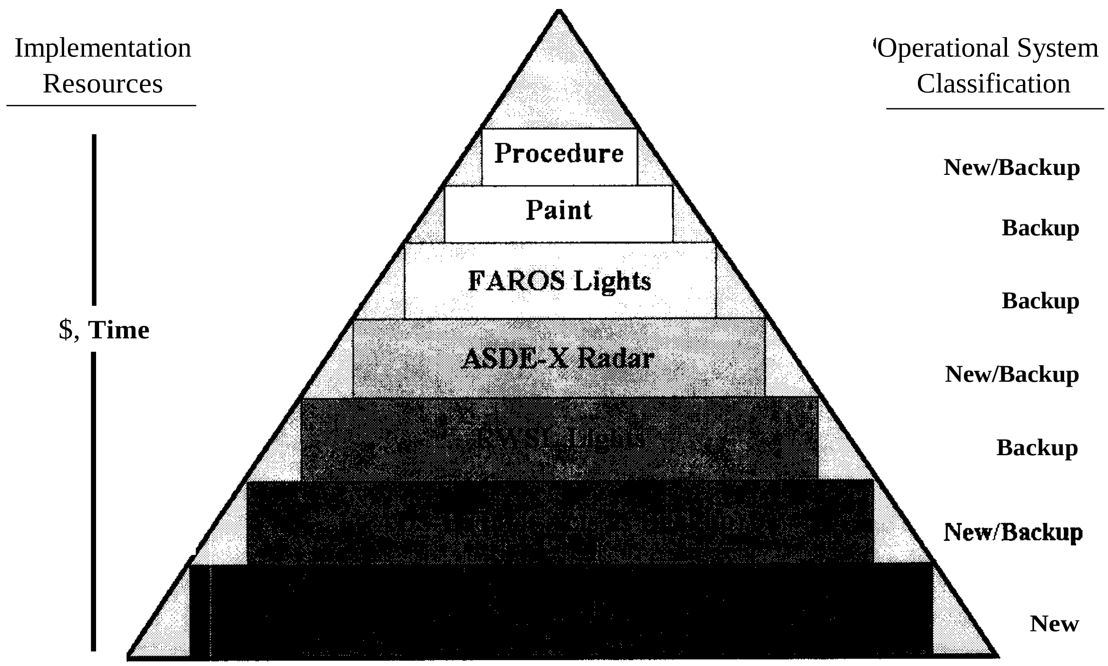



**Figure 1: Hierarchy of currently proposed runway incursion system solutions**

For technical descriptions and specification of each of the above technologies, the reader is referred to [6]-[11]. Along with these new components, the FAA is considering various new systems configurations that best exploit their advantages.

We begin our analysis by considering any ground traffic control system as the combination of both technology components (e.g., ASDE-X) and procedural components (e.g., visually monitoring from the control tower). In combination, these are used to direct movement on runways and taxiways in order to maintain necessary separation between aircraft on the airfield. Furthermore, we construct a framework that distinguishes different systems (i.e., combinations of technology and procedural components) by classifying them into one of the following categories:

*l Backup System Configuration, (BSC): which augments the current ground traffic control system, and will only be used in response to situations where the current system has permitted a potential incursion to occur. Accordingly, failure of these new, operationally independent system components would not impact the current ground traffic control system 's normal performance.*

*fl New System Configuration. (NSC): which modifies or replaces the current ground traffic control system, thereby fundamentally changing the way that it operates.*

Figure 1 includes a classification for each of the system solutions that we consider in this paper. Unlike BSC solutions, NSC solutions impact the primary response of the entire system, both technically and procedurally. Theoretically, they can either improve or reduce safety compared to the current system. On the other hand, BSC solutions are characterized as operationally independent of the main ground control system. Since they only come on line in the event that the principal system has failed to perform, they should improve or at least maintain the safety level of the primary system. The motivation for clearly distinguishing between the two system infrastructures is to recognize that the degree of testing required for assuring safety in each is dramatically different. At present, this distinction has not been recognized within the aviation community; however it is a crucial consideration that significantly impacts the amount of testing necessary for an emergent system solution.

We will show in this paper that while the current system for assuring aircraft safety on runways is considered as needing improvement, it is extremely difficult to rigorously show through testing that an NSC approach is better than the current system. As a result, we derive and recommend a strategy for addressing the runway incursion problem that advocates the initial installation of any new safety solution as a BSC. This approach requires much less testing for proof of added safety, and thereby permits earlier implementation of runway incursion prevention solutions.

We demonstrate that by extensively evaluating a new BSC while in actual operation, we can effectively project its safety performance for the case where it will operate in the role of an NSC. The length of this evaluation period depends on the airport under consideration and can be derived using a probabilistic analysis of rare events - in this case defined as Type A and B runway incursions (Section V). As part of establishing the evaluation requirements for safe introduction of new solutions, we have also developed an airport clustering concept that potentially permits the safe reduction of testing constraints by combining test results from different airports. The advantages and justifications for this approach are likewise discussed in (Section V).

While safety is the clear priority of our work, we also explore economic considerations, as they play an integral role in the realization of any substantial system infrastructure. We introduce an economic stakeholder analysis that reveals different financial viewpoints regarding the various technological system solutions (Section VI). Along with safety priorities, these economic disparities are taken into account as part of our recommended methodology for sequencing solution alternatives.

The overall approach we propose is not a novel technological invention or new operational procedure, as extensive background research has led us to believe that the currently investigated technologies (Fig. I) are extremely promising [6]-[28]. Our contribution lies in the development of a structured methodology for sequentially integrating new safety components into a runway incursion prevention system in a manner that provides scientifically sound and rigorously tested assurance of their safety benefits.

## III. Stakeholder Interactions

Many people have a direct interest in the success and safety of the ground traffic control system. The National Air Traffic Controller Association (NATCA), National Business Aviation Association (NBAA), Air Transport Association (ATA), Air Line Pilots Association (ALPA), and Aircraft Owners and Pilots Association (AOPA) are among the groups that represent the aviation community stakeholders. As part of their commitment to the overall safety of air transport, each of these institutions has an interest in runway incursion prevention. However, each has a different perspective on the solutions, based on their roles in the ground traffic control system and the economic impacts of solutions. The FAA works closely with these and other groups, in addition to representing passengers' interests within the aviation community.

As part of our research effort, the UVA team conducted interviews with safety representatives from several of the major stakeholder organizations (NATCA, ATA, ALPA, AOPA, NBAA) regarding their viewpoints on the runway incursion problem. In addition, the opinions and outlooks of several industry experts were consulted, among which were Mr. Wallace Feerrar of the MITRE Corporation and Mr. Randall Bailey of NASA. Their knowledge and perspective regarding research related to runway incursions, data collection methods and various ongoing initiatives for runway incursion prevention were a valuable source of insight and critical resource of information. The UVA team also met with Mr. Jim Nilo, director of operations at Richmond International Airport (RIC), to get a first hand account of how towered airports are operated. During this visit, we were able to meet with air traffic controllers and obtain their experienced perspective on various technological solutions. Mr. Terry Page, manager of the Washington Airports FAA district office was also on hand to answer the team's questions. Team members also reviewed the transcripts from the March 27, 2007 NTSB Public Forum on Runway Incursions. The key findings from our interactions with stakeholders and experts are:

1. The majority of the stakeholders expressed a unified concern that runway incursions are underreported and that a new system should be implemented in order to decrease the number of unreported incidents. This viewpoint is very important when considering the subject of new solutions. The less safe the current system is known to be, the lower the amount of testing that is required to prove that introducing a new solution improves the safety of the system. As a result, a change to the incursion reporting system that improves accuracy and shows larger numbers of A and B incursions would directly affect the amount of testing that would need to be done in order to validate the safety improvement offered by a new system. That is, the worse the current situation is, the easier (less testing) it is to rigorously show that a new solution is better.

2. The team also found some disparities between the ideas of the various stakeholders. One point of contention was that certain groups of stakeholders believe that the ground traffic control system will eventually move to a pilot-centric system for addressing runway incursions, at some point in the future. Advocates of this viewpoint believe that pilots, through use of cockpit traffic displays, may be able to provide improved ground traffic separation through

enhanced situation awareness. A second group of stakeholders believes that the ground traffic control system will remain a controller-centric system where the air traffic controllers manage the separation between aircraft.

3. There were concerns expressed regarding the degree of integrated system evaluation as opposed to technology component evaluation. These concerns were related to the ability to assure that new solutions will really add safety without more integrated operational tests.

4. Some solutions pose disparate levels of economic concern to various groups of stakeholders; they can not readily afford to pay as much as others for the level of increased safety provided to them. Though some technological solution components may yield secondary benefits to certain stakeholders, this project has only considered the economics of solutions implemented specifically to reduce runway incursions.

It is through directly addressing such issues that a solution to the runway mcurston problem will be reached. There is no packaged answer that immediately shows itself as best for everyone. Our analysis efforts address every one of the issues raised by stakeholders. However, today's answers will not persist. As our analysis of testing requirements will show, the sequence of steps to achieve an overall answer for improved safety will necessarily take a long time. During that time, things will continue to change. For example, as partial solutions make things better, it takes greater and greater effort to show that the next part of the overall solution adds even greater safety. Furthermore the costs for solutions will change over time, perhaps changing current value judgments of stakeholders. In addition, new solutions are likely to emerge, providing new opportunities for improvement. As a result, the FAA will need to have a continuous evaluation process to gather the experience and concerns provided by the various aviation stakeholders.

## IV. Literature Review

To better understand the runway incursion situation, we made use of several public databases containing records of aviation incidents in the United States [29], [30]. However, we found these databases to be incomplete and difficult to use. Our primary source of incursion data was the 2005 FAA Runway Safety Report, from which we were able to gather the number, type, severity, location, and year of individual incursions, but not a description of the incidents [31]. In addition to providing a detailed summary and analysis of data from 2001-2004, [31] also briefly presents a number of possible solutions to the runway incursion problem. To gain further insight into these solution alternatives, we reviewed FAA literature, equipment vendor information, academic publications, as well as the opinions of analysts and other users of technologies associated with runway incursion reduction [6]-[28]. A study of these documents revealed that each of these technologies and their different configurations can readily be categorized as a Backup System Configuration or a New System Configuration. However, nowhere in these documents was there recognition of the implications of different configurations on the ground traffic control system's safety. Because there has been no differentiation between BSCs and NSCs, we believe that the runway incursion problem is not being addressed as effectively as it might be.

To narrow the scope of our research, we reduced our analysis to include only the targeted 35 Operational Evolution Plan airports (OEP 35) and Category A and B incursion data. Our focus on the OEP 35 is justified by the fact that the FAA has identified these airports as the highest priority group for future strategic improvement and development [32]. Accounting for over 70% of the nation's commercial air traffic [32], OEP 35 airports inherently present the highest risk group for runway collisions in the National Airspace System (NAS) [5]. Limiting our safety analysis to evaluations of Category A and B incursions was based upon: I) information gathered from the FAA' s extensive 2007-2011 *Flight Plan* document, 2) interviews conducted with key players and experts within the aviation industry (see Section III), and 3) our own analysis of available incursion data. Based on these sources, we conclude that it is accepted industry practice to disregard Category C and D runway incursion data and to treat only Category A and B runway incursions as a basis for evaluating the risk of runway collisions. In order to further validate this assumption our own research concluded that there is no significant statistical correlation between the frequency of Type A/B incursions and Type *CID* incursions at the OEP 35 airports (Appendix G.l ).

Another important element of our research entailed surveying the established testing protocols and methods for various runway incursion prevention system components [6]-[28]. We found that none of these testing procedures included a statistical analysis component to determine the amount of testing that is required to ensure that the introduction of a New System Configuration would exceed the safety levels achieved by the current ground traffic control system. We frequently encountered literature that discussed only limited operational tests, with no mention of full system testing or unprecedented fault analysis [12], [27]. Chapter 9 of the *System Safety Handbook* [33] details the safety analysis techniques used to evaluate various aviation systems under the guidelines established by the FAA. However, inasmuch as this document refers to "system tests," it is important to note that its definition of "systems" (i.e. FAROS, RWSL, etc) is equivalent to our definition of "system components." Thus we have concluded that (33] only examines system component tests and fails to examine the fully integrated testing procedures for assuring safety of an overall system (i.e. the ground control traffic system). Likewise, the *Federal Aviation Administration Acquisition Management System-*

*Revision* describes general practice testing and evaluation methods without incorporating a holistic system testing discussion [34]. The lack of available information on full systems testing indicates that such tests are likely not being performed. Given that this assumption is valid, we are concerned that the introduction of new technologies and procedures which result in New System Configurations will not be adequately validated prior to acceptance for general operational use.

According to the FAA's latest *Runway Safety Blueprint*, the rate of Category A and B incursions was documented as 0.44 incursions per million operations in the fiscal year 2004. Since this value has not changed significantly over the course of the last three years [5], we infer that the probability of having a serious runway incursion is $4.4 \times 10^{-7}$. Historically, researchers have characterized events with probabilities on the order of $10^{-7}$ as rare events [35]. As a result, we have classified Category A and B runway incursions as rare events. Moreover, the probability of a rare event can be modeled using the binomial distribution [36), or the Poisson distribution [37), where the latter is an approximation of the binomial distribution for a large number of trials. For our probabilistic modeling of runway incursions, we present the results from the binomial distribution since it provides an exact value instead of an upper bound (from the Poisson distribution) [37]. However, our comparison of the results obtained by both methods showed them to be nearly identical. Based on these methods derived from a review of the literature on probabilistic analysis of rare events, we are able to determine the amount of testing required to provide a desired likelihood that a New System Configuration is safer than the system it replaces.

In further consideration of the issues associated with testing a safety system, we found that none of the literature reviewed claims that certain sets of airports are similar to the extent that conclusions reached from testing at one airport apply to others [6]-[28]. While literature on the testing of various runway incursion technologies seems to imply that validation at one airport is applicable to all others, we have found no published methods that support this conclusion, when extended to the safety provided by an overall ground traffic control system. Conversely, the study presented to the UVA team on February 27, 2007 by Mr. Wally Feerrar of MITRE Corporation showed that there is no firmly established set of direct causal factors for runway incursions. Of the more than 150 variables evaluated in MITRE's analysis, only three: the number of operations, the existence of an air traffic control tower, and the number of runway crossings, were shown to significantly affect the runway incursion risk at an airport [38], [39]. Out of these three, Mr. Feerrar stated that towered airports and airports with numerous runway crossings implicitly have more aircraft operations. This implies that the variables are not independent, since the airports with more operations have an inherently higher risk for runway incursions. Our own investigation found that the number of runway crossings at the OEP 35 airports ranges from zero to six, and can not alone explain the variation in the rates of incursions over the data set [39]. Without having an accepted causal model for runway incursions, validating an NSC at any one airport does not necessarily imply that the results hold for that same NSC at any other airport.

If testing at one airport can not provide assurance of safety at other airports it follows that testing at every airport would be required. Therefore we investigated clustering analyses as a means of reducing necessary testing. Clustering merges multiple variables into a single categorical variable that identifies groups of observations [40]. This in turn, enables the qualitative measurement of the relevant differences between objects and effectively partitions the data into similar groups [41]. Clustering allows for the possibility that the test results collected at a particular airport may be extended to other airports that share similar characteristics, therefore reducing the overall number of tests required across the NAS.

Reducing testing is one way to mitigate financial barriers to adoption of new solutions. To fully understand the financial factors with new system components we developed an economic analysis to assess each system component because a solution, no matter how good, can not be implemented without funding. The objective is to determine if the cost to a particular aviation stakeholder group would prevent them from safely and efficiently participating in the NAS. We collected cost information from a variety of sources to project the cost borne by each of the different stakeholders for the different system components (see Appendix G.5).

As a result of our review of the literature related to runway incursions, safety systems, and economic analyses we are able to draw the following main conclusions:

1. There exist a number of promising technologies in varying stages of development that can provide the basis for ground traffic control systems and improve their safety.

2. Despite its strong focus on technology development, the FAA has not explicitly characterized runway incursion system solutions based on their operational implications to the current ground traffic control system.

3. The FAA has not made use of statistical analysis of rare events to adequately determine the testing requirements which are necessary to validate a new solution's effect on the safety of the current ground traffic control system.

4. The available literature dealing with the testing of different runway incursion technologies has not provided sufficient verification that successful tests at one airport are fully applicable to other airports.

**V. System Analysis**

As previously established, new technological and procedural components can be implemented as New Systems Configurations or as Backup System Configurations. For BSCs, testing can follow the FAA model as the current system is unchanged, and it is only necessary to show that the backup modes work properly when the principle system fails (imminent runway incursion). However, for those components that would change the existing ground traffic control system, testing must be conducted to provide assurance that safety has not been negatively altered. In this section, we present an analysis of the amount of testing required to meet various safety assurance levels relative to the current system, as well as a technique to effectively reduce those testing levels.

*Statistical Analysis*

To determine the amount of testing required to indicate that any New System Configuration is at least as safe as the system it is replacing, we use a probability analysis based on the binomial distribution. The probability of a binomially distributed sequence of events is expressed as

$$P(X \le x) = \sum_{y=0}^{x} \binom{n}{y} p^{y} (1-p)^{n-y} \qquad (1)$$

[37] where $p$ is the observed rate of A and B runway incursions (incursions per million operations), n is the number of aircraft operations and x is the number of incursions that occur. There are two items of interest that can be derived from this:

1) The predicted probability that the incursion rate for the New System Configuration is lower than the rates for the current ground traffic control system. We clearly want the New

System Configuration rate observed through testing to be less than that of the current ground traffic control system.

**2)** The comparison of the predicted incursion rate for the New System Configuration and the historical incursion rates.

Using the above formula, we performed an analysis that solves for the number of test operations necessary to provide a particular likelihood (i.e. 95%, 75% etc.) that the tested system will be better than the current ground traffic control system. For this analysis, the results for the amount of required testing depend on how many incursions are actually observed during testing: i.e., if no incursions occur during testing, then less operations are needed in the test period than would be needed if one or more incursions are observed during testing. For example, the current historical probability for A and B runway incursions at Chicago O'Hare International (ORD) and Atlanta Hartsfield-Jackson International (ATL) airports is one A and B incursion in 1,236,648 operations [31]. Using the binomial distribution our analysis determines the minimum amount of test operations that would ensure 95% likelihood that a New System Configuration is better than the current ground traffic control system. In this particular case the number of test operations that would be required, assuming that neither an A nor B runway incursion is observed during test, would be 3,704,385. At current operations rates, an average of 4 years of test operations at ORD and ATL would be required to assure this improvement.

We grouped the OEP 35 airports into four categories based upon their operations levels to account for the variability in airports; this was done to illustrate the relationship between average operations rates at the airports and the length of the required test period. Appendix G. 2 shows the actual groupings used for this analysis. The failure rates for the four tiers are shown in Table 5.1.

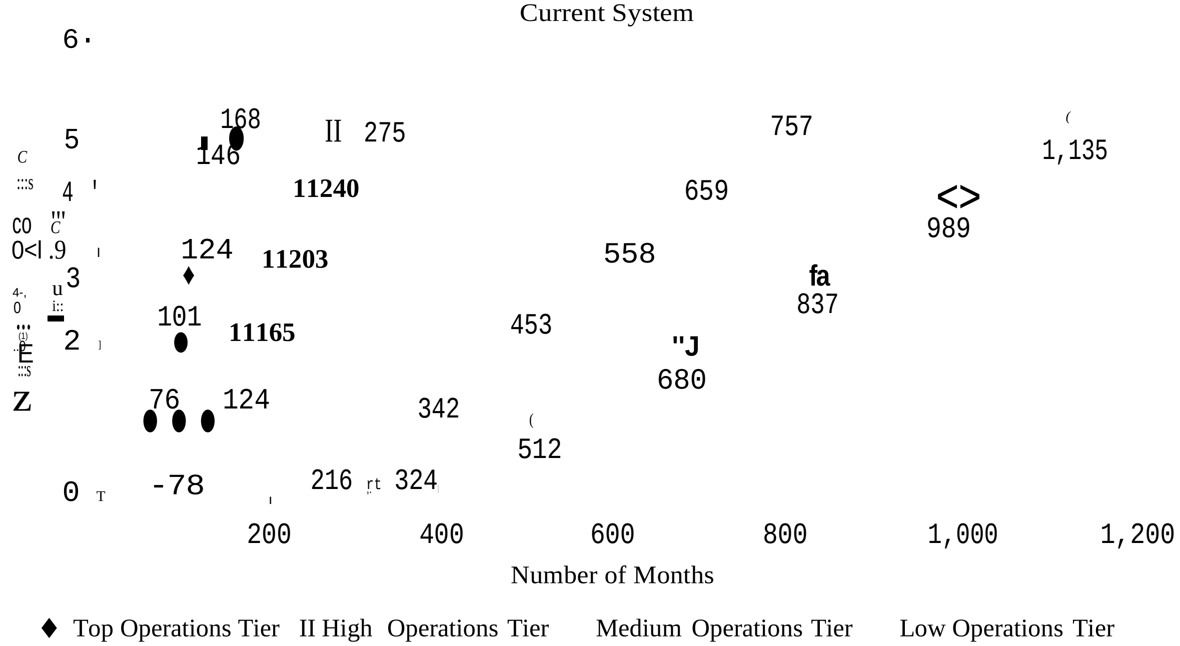
| OEP 35 Groups | A&BRunway Incursion Probabilicy |
|---|---|
| Top Operations Tier | 8.09 x } O·/ |
| High Operations Tier | 9.00 x } 0·¹ |
| Medium Operations Tier | 5.08 x 10·¹ |
| Low Operations Tier | 8.20 x 10-/ |

**Table 5.1: Runway Incursion Probability at OEP 35 Airport Groups**

There is only a slight difference among the four different average incursion rates. Nonetheless, the level of operations at a low tier versus the top tier will have a large impact in translating the number of test operations into months of operations. For example, the low tier would require 3.6 million test operations while the top tier, ORD and ATL, require 3.7 million operations. This difference is due to the slight difference in incursion rates. However, for an average low tier airport this translates into 27 years of test operations versus 4 years of testing at the top tier.

The following graphs illustrate the amount of testing required by translating the required amount of test operations into the months of average airport operations. This is calculated for possible testing scenarios where either 0, 1, 2, or 3 A or B runway incursions occur during the test period. This was calculated by dividing the total number of operations required for testing (obtained through application of the binomial probability distribution) by the average number of operations per month for each tier. Figure 5.1 shows the number of months of testing required to provide a 95% likelihood that the NSC has a lower failure rate than the system it replaces.

Figure **5.1:** Testing Periods for a 95% Likelihood of Safety Improvement to Current System




In other words, it depicts the length of testing required for a given number of observed A and B runway incursions during the testing period. The x-axis shows the number of months of testing. For the high operations tier airports, for example, it is expected that if no runway incursion occurred during the testing period it would take 78 months of operations to have a 95% likelihood that the New System Configuration provides an improvement in safety. If three incursions occur during the test period, a 124-month testing program would be required for assuring improvement in safety. On the other hand, for medium operations tier airports, if no runway incursion occurred during the testing period it would take 216 months of operations to have a 95% likelihood the New System Configuration provided an improvement in safety. As the operations rates decrease, the necessary testing period increases dramatically; a consequence of dealing with rare events. This illustrates how difficult it can be to assure that a New System Configuration will actually improve upon the system it replaces.

**Figure 5.2 Testing Period for a 75% Likelihood of Safety Improvement to the Current System**

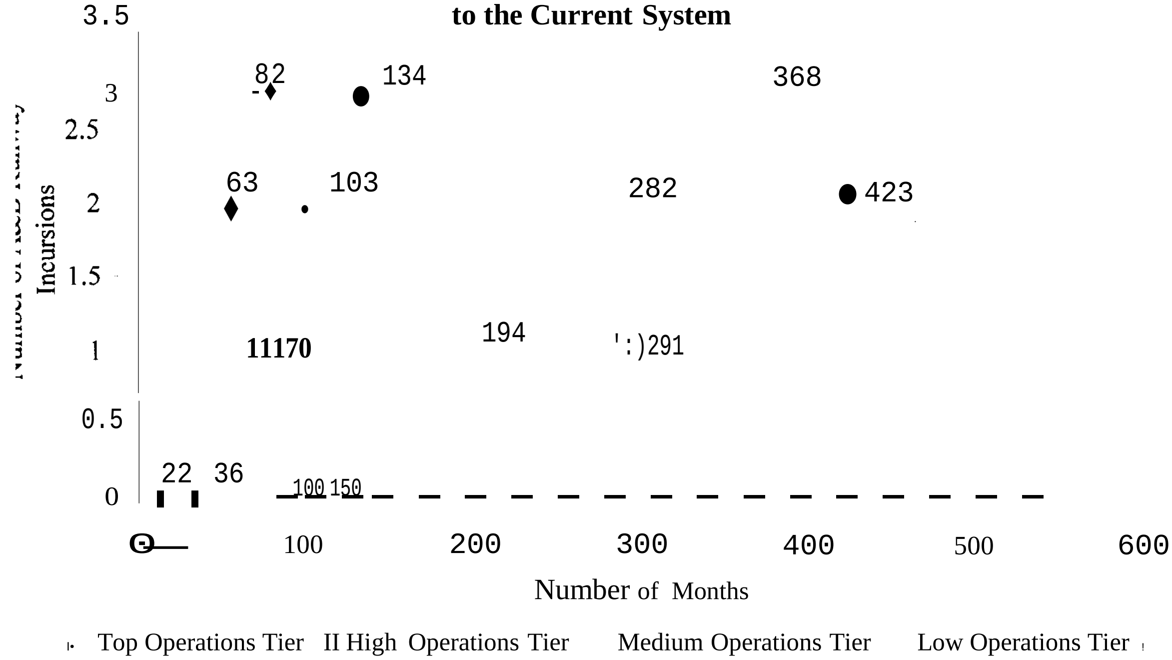
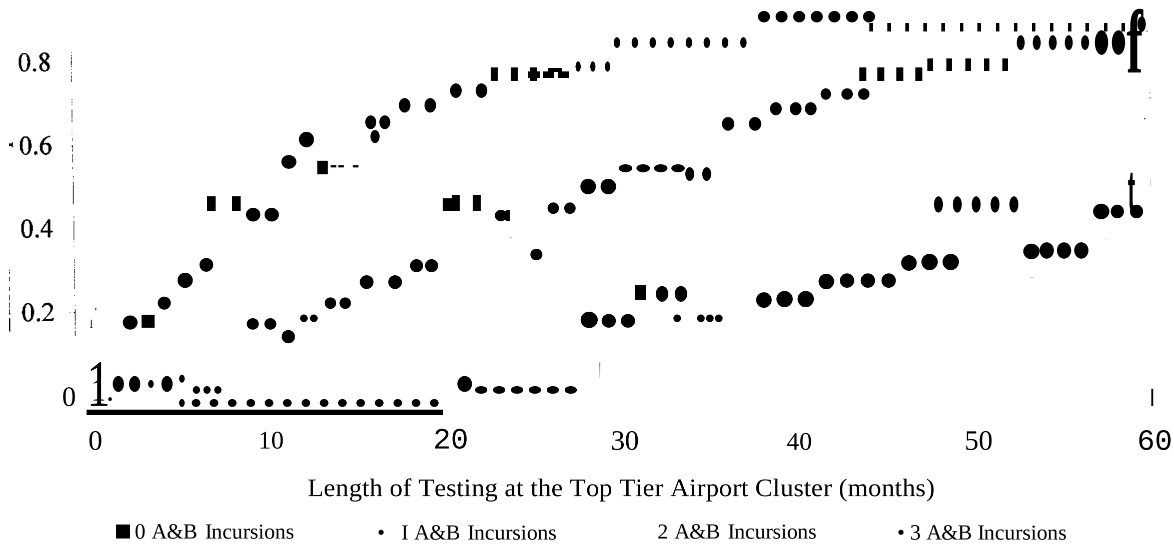



Figure 5.2 shows the number of months of testing required to provide a 75% likelihood the new system has an equivalent of lower failure rate, a lower level of assurance of achieving safety improvements. Figure 5.2 illustrates that a reduction in the length of the test period can be attained by reducing the assurance levels. For our example, assuming ORD had three observed incursions during the test period, the test period is reduced from 124 months to 82 months at the expense of a 20% reduction in assurance level.

Figure 5.3 illustrates for the top tier operations airports how assurance level increases as the number of months of operations in the test period increases, given an assumed number of A and B runway incursions observed during the test period. The x-axis of the graph is the number of months of test operations while the y-axis shows the likelihood that the system being tested has a lower rate of failure than the ground traffic control system it replaces. For example, at 48 months having observed zero A and B runway incursions, the likelihood that the New System

Configuration will improve safety is 95%, but if two A and B type runway mcurs1ons are observed that likelihood drops to 57%.

**Figure 5.3 Growth in Likelihood of Improvement During Testing Period**




As shown in this analysis, the required testing periods for New System Configurations result in prohibitively long test periods.

We now explore Backup System Configuration testing. Equation 2 explains the relationship between the probability of runway incursions of the ground traffic control system and the Backup System Configuration.

*P(Incursion) = P(Incursionl Base system)*P(Incursion in BSCI Incursion in Base System)* (2)

In this equation the probability of an incursion in the base system is being reduced by the probability of that incursion occurring in spite of the backup system's response. Both the base system and the backup system must fail to result in an incursion. When a component is implemented in a New System Configuration it does not benefit from this redundancy.

For example, if the RWSL or FAROS is introduced into use, they would supplement the current air traffic control process for ground operations and thus meet our definition of a Backup System Configuration. The components will come into play only when an imminent incursion situation is observed. A proper detection by the system is a sign that the normal low likelihood of an incursion (5 incursions per 257 million operations [31]) has significantly risen (many orders of magnitude) for the flight in question. As a result of the BCS detection, a missed approach (the recommended FAA course of action) is executed by the approaching aircraft. A missed approach is a standard procedure available to a pilot who is cleared to land [42] and therefore its likelihood of leading to a dangerous situation is known to be acceptably low; much lower than the risk of the imminent incursion situation at that point in time. Overall, the RWSL system does not interfere with the basic system for ground operations. To prove its value one must only demonstrate that false alert rates are acceptably low, detection rates for incursions are high and that missed approaches are safe.

Our calculations show that for top tier operations airports the current incursion rate is 0.81 per million operations. If 90% of imminent incursions are detected, the integrated traffic control system will operate at a 0.081 incursions per million operations rate, a substantial improvement. Demonstration through testing that a 90% rate is achievable requires a relatively limited test program. Since it does not replace the existing system, no proofs are required that relate to the incursion rates of the current system, thereby avoiding a major test program.

As a result of the analyses presented above, we recommend that new solutions designed to increase runway safety be initially implemented in Backup System Configurations that do not significantly alter the current ground traffic control system. As Backup System Configurations there would be much less stringent testing requirements to implementing the components, allowing any potential benefits the components provide to be realized sooner. Additionally, data could be collected over time on the Backup System Configuration while it is in operation. This data collection could be used to help determine if its performance would be a sufficient basis for a new traffic control system configuration and could serve to reduce test time for making a transition to a new primary status. Figure 5.3 could serve as a guide for determining when a certain level of assurance had been gained in the Backup System Configuration.

A consequence of the FAA's sequential strategy for introducing a number of new solutions into the system is that late additions will have to meet even more stringent assurance levels to meet if previously incorporated components are successful at reducing the likelihood of runway incursions. Thus, implementation in Backup System Configurations will become even more attractive as the required test periods grow as initial safety levels improve.

We conclude then that our statistical analysis shows that it would take very extensive testing periods (several years) to assure that a New System Configuration improves the safety levels achieved by the current ground traffic control system. This result leads us to a recommendation that new system components should first be introduced as part of Backup System Configurations to augment the current ground traffic control system. This approach would reduce the safety validation requirements for these parts of the overall system, since they would only need to be shown as not adversely impacting the current ground traffic control system's normal performance while serving as a backup. This would permit testing periods that are significantly shorter in duration, while achieving the desired confidence in the overall system's ability to increase safety and capturing the potential benefits from these new technology components.

*Airport Clustering Analysis*

We have shown that the time and cost needed to rigorously prove that the safety system will be improved by a New System Configuration could be prohibitive. Using a technique called clustering analysis, we suggest the amount of system testing can be significantly reduced without sacrificing the necessary safety assurances.

Clustering analysis groups objects by defined variables to maximize similarity within a cluster and minimize similarity between different clusters [43] (see Appendix G.3 for detailed explanation of clustering analysis). Clustering offers many advantages: 1) unlike a regression analysis, there is no need for initial assumptions, 2) it simplifies a large number of observations into basic groupings, 3) it can use as many, or as few, variables as desired, 4) the decision-maker has freedom to determine the level of similarity and differentiation that is desired, and 5) it provides an excellent visual representation via the use of clustering trees.

As discussed in the Literature Review, testing done at one airport can not necessarily be used at another airport. This idea is readily illustrated by Figure 5.4, which shows the difference in the physical configurations at two of the OEP 35 airports. However, clustering analysis provides a quantitative method for determining similarities and differences between airports. When airports are sufficiently similar, it is then a reasonable proposition to test at the worst performing airport in the cluster, and use those results to approximate expected performance for the remainder of the airports in that cluster. This alleviates the need for the alternative - each airport requiring its own unique test program. While we do not have sufficient data or operational experience to carry out a credible airport cluster analysis for runway incursions, we conduct a hypothetical analysis to gauge the impact of clustering on test requirements.

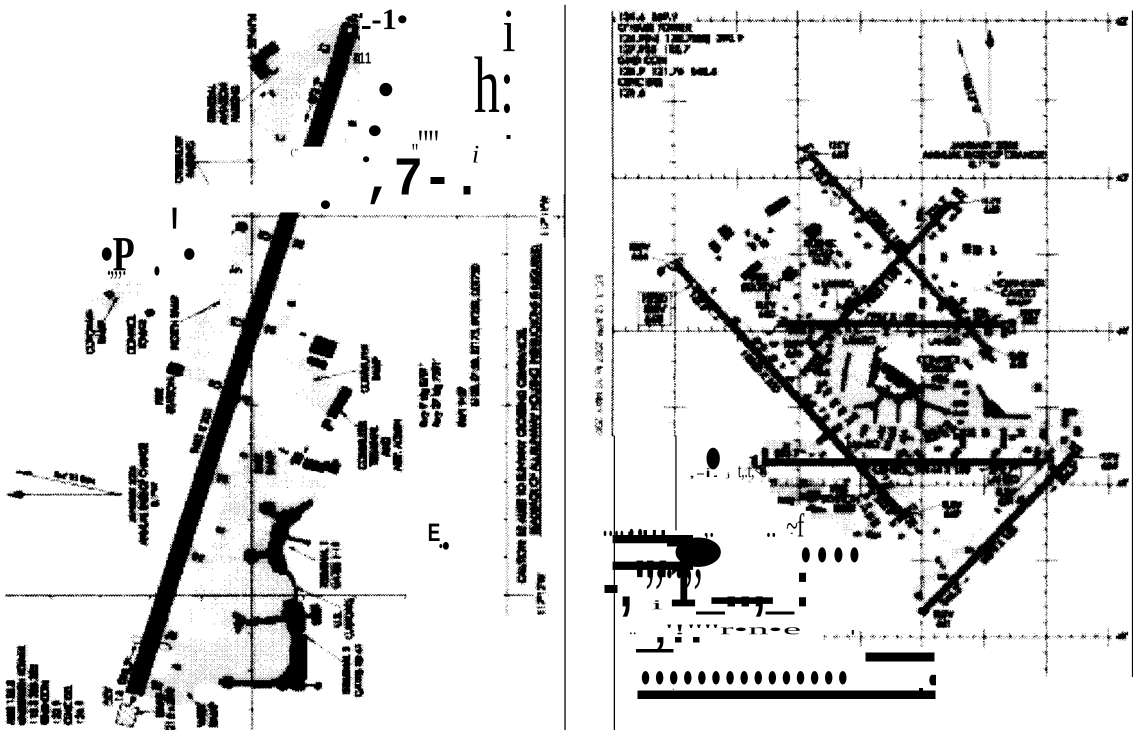


**Figure 5.4: Comparison of airport size and runway configuration from San Diego International Airport (left) and Chicago O'Hare International Airport (right) [source: FAA].**

For our clustering analysis we aimed to isolate the relevant characteristics of an airport that could be major sources of risk for runway incursions at OEP 35 Airports. We found, through our discussions with industry and stakeholder representatives, that factors such as the number of operations and airport geometry are worthwhile aspects to consider as potential causes of runway incursions [38]. In [31] it was also suggested that GA aircraft were involved in a disproportionate number of runway incursions. Based on this understanding, we developed a set of variables to be used in our first clustering example shown in Table 5.3.

The first four variables incorporate airport operations and runway complexity and the fifth variable incorporates pilot capabilities and experience. While these variables were logically chosen, we do not claim that this is necessarily a complete solution. The FAA, with better access to data on runway incursion, would be able to generate a more inclusive list of variables to be used in a clustering analysis by performing an analysis from its collection of historical data on runway incursion incidents.

| Variables | Rationale |
|---|---|
| **Number of operations** | This variable accounts for the level of total traffic volume at each airport |
| **Number of runways** | This variable is one measure of the geometric complexity of the airport. |
| **Number of crossing runways** | Crossing runways offer potential for runway incursions either during high tempo operations for landing/takeoff, or when a runway is used as a taxi route. |
| **Number of taxiways that intersect runways** | This variable also accounts for the geometric complexity of the airport. Many hot spots (trouble spots for runway incursions) are at locations where taxiways intersect with runways. |
| **Percent commercial, GA and military** | The types of aircraft that use an airfield may be indicative of differing levels of pilot experience, knowledge and familiarity with the high traffic OEP 35 operations. Runway incursion rates may be affected by the mix of these differing types of users interacting in the same environment. |

**Table 5.3: Variables for Clustering Analysis**

In addition, we standardized our variables and applied equal weight to all variables. Another decision-maker may choose to assign different weights among their identified variables to account for the variables' relative impacts on runway incursions.

The output of a clustering analysis is a tree-like structure graphically depicting the degree to which inputs are related. After making a decision about the level of similarity required among inputs, an analyst can use this representation to determine which branches can be grouped together. The height on the vertical axis is a reference for how similar objects are (most similar at height zero). Figures 5.5 and 5.6 illustrate different ways one can group objects based on the same set of inputs. Figure 5.5 shows groupings that are less similar, where the height on the vertical axis indicates similarity (equality implying height= 0), and the x-axis represents each of OEP 35 Airports numbered according to Appendix G.3.

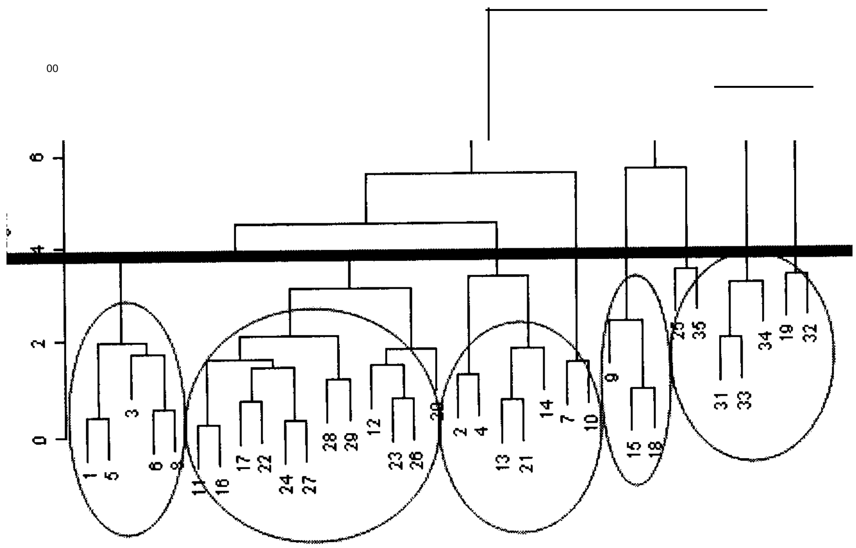



**Figure 5.5: Example of clustering performed using the variables in Table 5.3.**

Figure 5.6 shows more similar groupings. We can additionally infer that a less strict value for similarity (height) allows for the use of fewer groups to include each of the inputs. The apparent differences between the two examples reveal the critical role of the decision-maker in determining the necessary degree of similarity between cluster members, as measured by height.

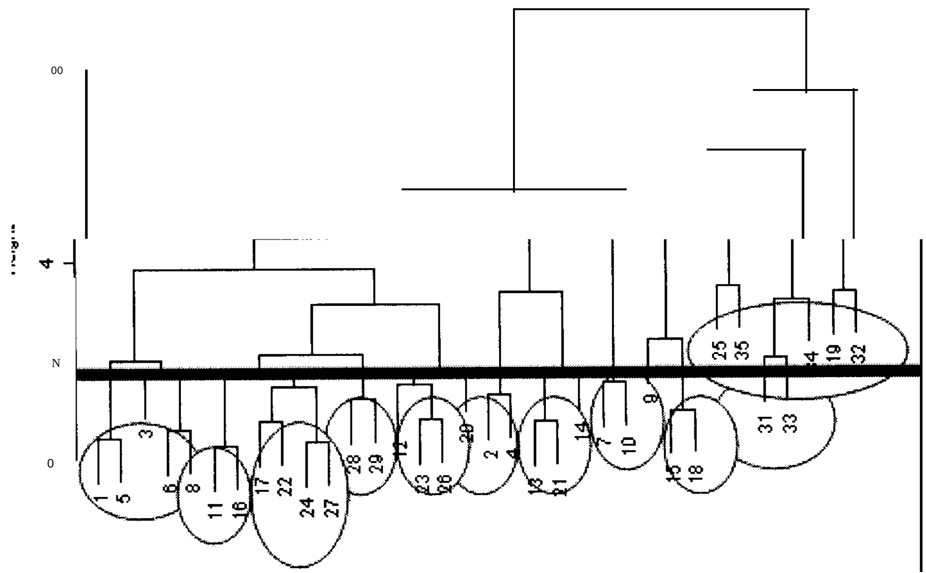


**Figure 5.6: Example of clustering with the same variables as Fig. 5.5 but showing greater similarity**

While clusters can be based on a wide array of characteristics for each airport, the number of variables used in the analysis can be narrowed when evaluating a specific solution, because it is accepted that certain airport variables may not affect the performance of certain solutions. To illustrate this concept we applied our clustering methodology to the FAROS technology component. Since this system uses inductive loop sensors in the vicinity of crossing runways and taxiways, we used those variables, in addition to traffic volume, for the OEP 35 airports cluster analysis. General Aviation (GA) aircraft is not used as a variable in the analysis because, for the sake of example, it is assumed that FAROS performance would not be sensitive to the type of aircraft and experience of the pilot.

Figure 5.7 shows the results of this analysis based on clustering using the following variables: number of crossing runways, number of intersecting taxiways, and number of operations for each of the OEP 35 airports Appendix G.3. We determined that there are four different clusters and one outlier indicating five test airports would need to be identified. Based on this result, we would advocate testing FAROS at the airport within each cluster that has the highest rate of runway incursions. For example, within Cluster B, Sky Harbor International

Airport, Phoenix (PHX) has the highest A and B runway incursion rate (.9525 incidents per million operations) [31]. We choose the airports with the highest rate of incursions because the more frequently incursions occur, the less time it would take to validate the new solution, as discussed in our analysis on the length of testing period.

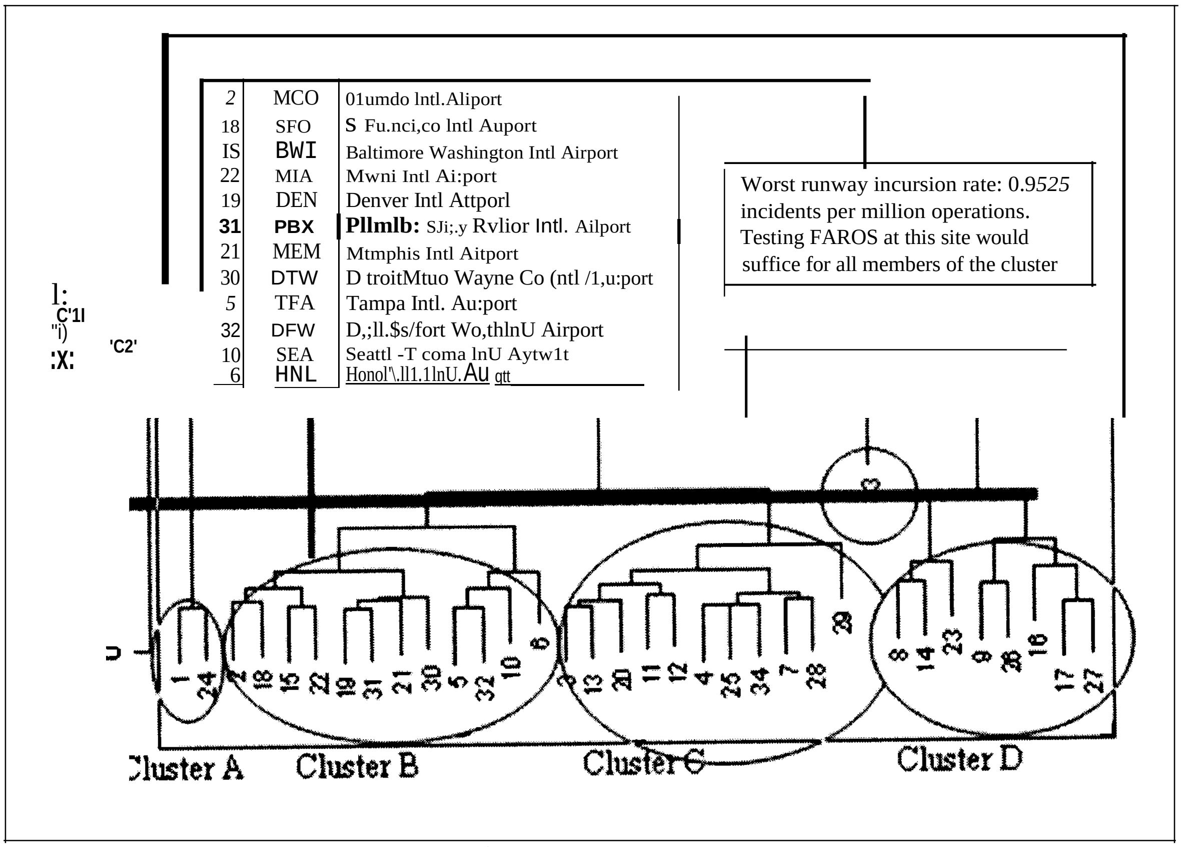



**Figure 5.7: Clustering example for FAROS (see Appendix G.3 for additional information).**

The final result of the clustering analysis is that we reduce the number of test sites by over 85% in our example (by reducing testing from 35 airports to 5 airports), while s i1! meeting the rigorous testing required to show that safety will be improved. These results indicate that clustering techniques can reduce testing, and can be a vital component in leveraging completed test results to other airports that have not yet implemented new technologies or have been hesitant to risk the possibility of reducing their current level of safety.

### *VI. Economic Impacts and Implications*

This section analyzes the impacts and implications of the different costs that each major aviation stakeholder group incurs as a function of the solution under consideration. The costs presented below were calculated based upon available data for OEP 35 airports, and are computed on an annual basis. These rough order of magnitude costs give an idea of the relative financial burden placed on each member of the aviation community. Appendix G.5. contains information as to how this table was constructed. The costs presented for passengers are not directly charged, but we assume that they will indirectly end up paying the cost through either airport fees or ticket prices.

| **STAKEHOLDERS** | **ASDE-X** | **ADS-B** | | **FAROS** | **RWSL** | **PAINT** |
|---|---|---|---|---|---|---|
| **Per Passenger** | $0.09 | $9.91 | | $0.02 | **$0.07** | **$0.003** |
| **Commercial A.irliltts** | | **LOWN'** | **UpJ)el'** | | | |
| **(per flight)** | $0.66 | $13.89 | $46.47 | $0.14 | $0.50 | **$0.022** |
| **(per aircraft)** | | $14,700 | $50,000 | | | |
| **Gt11t1·al A,1ation** | | Lower | Upper | | | |
| **(per flight)** | $0.62 | $9.80 | *$272.00* | $0.13 | $0.48 | **$0.021** |
| **(per aircraft)** | | $875.00 | *$25,000* | | | |
| **Avg. OEP35 AiI1101't** | $325,000 | $150,000 | | $70,000 | **$250,000** | **$10,700** |
| (% **ofoperating budget)** | 0.07°0 | O.OJ0·o | | 0.0l ··o | 0.05% | **0.002%** |

**Table 6.1: Stakeholder Economic Analysis (computed on an annual basis)**

As is readily portrayed by the Table 6.1, passengers receive a lot of benefit from the implementation of all systems at relatively little cost, with the exception of ADS-B. It is likely most passengers would not balk at paying a few extra cents for reducing the chance of being involved in a collision, however it is unknown as to whether they would choose to pay $10 per leg, when strong odds are that the flight will be uneventful (there have been 5 collisions in 257 million operations over a period of 4 years) [44].

Several other important factors should be kept in mind when considering these results. Foremost, as system components are implemented, the runway incursion rate should decrease. Should the runway incursion rate decline significantly, it could be more difficult to rationalize solutions that are implemented later and at the same time pose economic stress to any or all stakeholders. Such is the case for ADS-B, as it will likely be implemented at a later date than many of the other solution components. As the table shows, the general aviation community stands to shoulder a relatively heavy cost, when compared to other stakeholders, to implement this technology. As this may take place after intermediate systems (FAROS, RWSL, paint, etc.) are already implemented, the further reductions in runway incursions will likely be extremely low for the relatively high cost of the system to the general aviation stakeholders. If it can be shown that a ground traffic control system in which not all aircraft are equipped with ADS-B would have worth, ADS-B could be initially implemented as a Backup System Configuration with less burden placed on general aviation stakeholders. This would allow more time to prove the value of ADS-B as well as allow the cost of ADS-B to possibly be reduced to such an extent that would encourage equipage. If implementing ADS-B without full equipage as a Backup System Configuration is not feasible, the FAA should consider investing in research and development to lower the cost of ADS-B avionics, making a mandated implementation more attractive to the most economically impacted stakeholder groups.

Another important factor to note is that none of the costs shown above include system testing. As discussed earlier in this paper, system components implemented further in the future will require more testing to ensure that they are safer than the then current, and hopefully improved, method of operation, so as to not induce higher risks. The more testing required, the higher the costs to each stakeholder.

Airports bear a diverse range of costs for various FAA mandated technologies based on many factors, such as their traffic volume. These system costs, as with many other airport costs, are generally recouped by way of landing fees [45]. These landing fees are incorporated into the commercial and general aviation costs.

This analysis points to the relatively high cost to general aviation. Recognizing that: 1) only about 5% of the flights at the OEP 35 airports are general aviation flights, and 2) by the time ADS-B becomes a new system option the safety level for incursions is likely to be much improved, we recommend that an important avenue for FAA consideration is to explore ground traffic control system viability of a 95% ADS-B equipped aircraft population at OEP 35 airports. Through this research activity the FAA can determine necessity or feasibility of possible future mandates and weigh economic costs to stakeholders versus the benefit gained.

*Implementation Sequencing Strategies*

From the system implementation perspective, airport clustering is both a time-saving and financially efficient strategy. Airports, which might have otherwise been prevented from investigating a new system, would benefit from the test data collected at other similar airports within their cluster. Nevertheless, access to this information alone would not be sufficient to determine the implementation strategy for an individual airport. Since the FAA is investing in a variety of solutions, individual airports are afforded the flexibility to select the solution that most closely meets their needs.

The different paths in Figure 6.1 represent various sequential implementation strategies for a smaller OEP 35 airport operating at lower traffic volume. Depending on the operational characteristics of an airport, a certain strategy may yield greater value than any other.

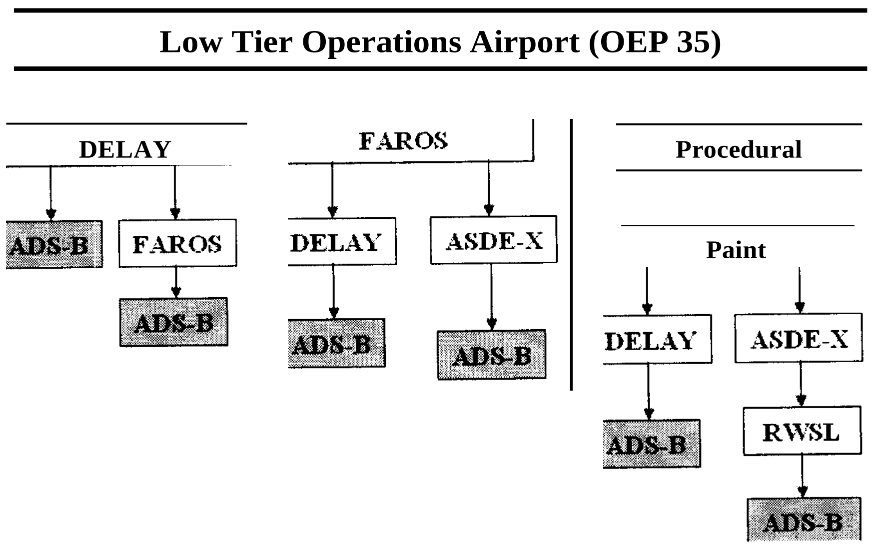



**Figure 6.1: Potential system solution paths for Low Tier Operations (OEP 35) airport**

For an airport that has never had a Type A or B runway incursion (such as a lower volume airport within the OEP 35), choosing to delay implementation of a new system until extensive testing from a similar airport validates its effectiveness, may be the wisest strategy. On the other hand, an airport with similar physical and operational characteristics that has previously experienced serious runway incursions may be more inclined towards more immediate action, such as implementing a BSC solution (i.e. FAROS). Of the two airports, the former benefits by selecting the delayed path, since the second airport's test data provides the necessary safety assurances prior to implementation. Additionally, the latter airport gains a much needed improvement in safety to prevent its runway collision risk from growing as a result of inaction.

In contrast, when considering large, high-volume airports, a new set of strategy selection criteria come into play. Unlike in Figure 6.1, none of the paths in Figure 6.2 involve a component for which there would be a strategic delay.

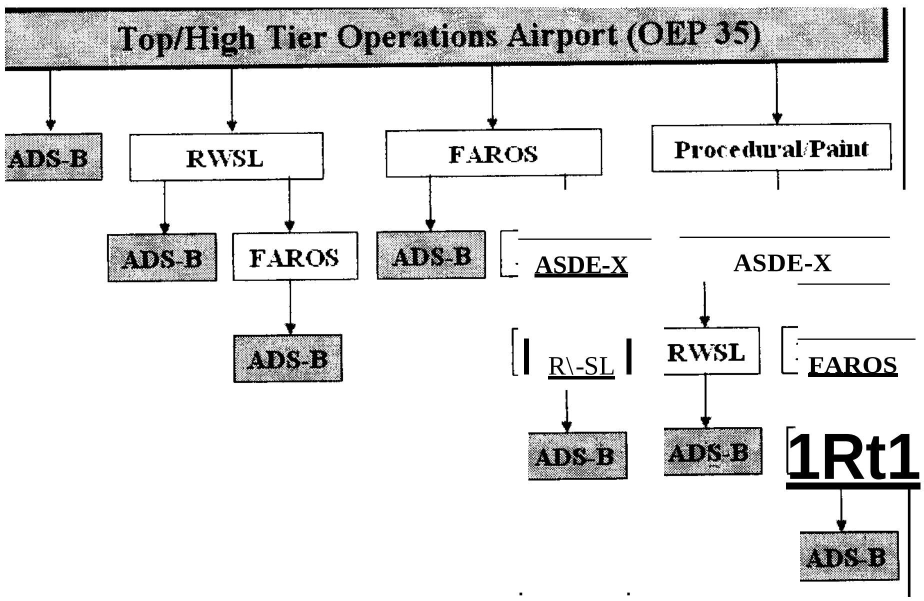



**Figure 6.2: Potential system solution paths for Low Tier Operations (OEP 35) airport**

Several of the OEP 35 airports also make up the FAA's Focus-35 list which identifies the airports with the highest reported annual rates of runway incursions [31]. The airports common to both lists reside on the higher end of operational volume within the OEP 35. Consequently, an ASDE-X equipped OEP 35 airport located at the top of the Focus-35 list has a much greater incentive to take immediate action and implement a large-scale Backup System Configuration, than to delay action until the corresponding testing data becomes available. Other lower-tier OEP 35 airports may choose to delay implementation while more assurance data is collected at the early adoption sites; however this depends on their current safety record with respect to Type A and B runway incursions.

The benefit to the NAS resulting from a flexible, hierarchical network of solutions is multifaceted. It addresses both the safety and economic concerns of airports with the most pressing needs, while channeling the necessary testing information to airports with less immediate concerns. In this way, later implementations can be put into practice with higher confidence of improving existing safety.

**VII. Conclusions and Recommendations**

*Conclusions*

The FAA is considering many new components and system component configurations to improve the runway incursion and collision rates for the current ground traffic control system. We have classified these solutions into two categories:

1) Backup System Configurations which augment the current ground traffic control system, and will initially only be used to respond to situations where the current system has permitted a potential incursion to occur. Accordingly, failure of these new, operationally independent system component would not impact the current ground traffic control system's performance, and

2) New Systems Configurations, where a new system component changes normal operations of the current ground traffic control system.

We show that these two classes of solutions require dramatically different degrees of testing and, at present, the FAA plans do not show sensitivity to this difference as discussed in Section IV.

Sensitivity to this difference is paramount to accurately determining the amount of testing required for a new solution, and for the case of New System Configurations, data requirements should be determined through statistical analysis methods related to rare events as discussed in Section V. If the FAA were to use this type of statistical analysis to test a New System Configuration's increased safety benefit, based on our results, it would take a very long period of testing to show a high likelihood of reducing A or B incursions below current levels. These results motivate the introduction of new solutions as Backup System Configurations, and correspondingly discourage their immediate introduction as New System Configurations. Correspondingly, the FAA can introduce a new solution as a Backup System Configuration to augment the current ground traffic system, and during this mode of operation collect sufficient data to assure performance in the role of a New System Configuration. For example, one could introduce the use of ASDE-X as part of a controller alerting system for cases of imminent incidents and only after suitable evaluation in that mode, using the system as the primary surveillance system for controlling ground traffic.

Another key aspect to our analysis shows that validating a system solution through testing at any one OEP 35 location does not necessarily validate that system solution at the remaining 34 airports. Our literature review and interactions with key aviation organizations indicates that there exist numerous factors which contribute to runway incursions at the OEP 35 (e.g., traffic level, runway configuration, commercial/general aviation mix), but to-date, no airport specific cause and effect relationship has been firmly asserted. Because of the diversity of these attributes, for example, a test conducted at Fort Lauderdale - Hollywood International Airport could not be deemed to be valid at a much larger, and more complexly configured airfield, such as Chicago O'Hare International Airport, and vice versa.

To alleviate the burden of expansive testing, a promising technique for future FAA investigation is statistical clustering. This technique, by analytically correlating groups of airports as similar with regard to runway incursions, would allow the FAA to confidently leverage test results across similar airports. This integrated testing process would decrease overall testing, while still maintaining the necessary high level of assurance required for the new safety system. In order to gain an understanding of the test reduction possibilities, we conducted a sample analysis of FAROS for the OEP 35 airports. Our analysis resulted in five airport clusters, and a corresponding 85% reduction in testing. However, cluster variable selection must be strategically justified and sufficiently conservative to ensure that the resulting clusters are created on the basis of relevant similarities from a runway incursion perspective. We believe that the FAA can carry out the efforts to better understand the ability to use clustering as part of their test concept for introducing runway incursion systems.

Our analysis also recognizes that sequential implementation of new solutions should result in the safety standards of the ground traffic control system continually increasing. This makes validation of improved safety through use of new system components that are introduced later in the sequence increasingly more difficult. For this reason, there are challenging obstacles for advocates of a pilot-centric ADS-B system, since this component is not likely to be available for use until other solutions have already been placed into use. As a result, this kind of system would require an even greater degree of testing before being safely introduced as a New System Configuration for ground traffic control system in the NAS.

There are also various economic consequences to stakeholder groups for all proposed system component solutions. For nearer term solutions, our analysis indicates that no stakeholder group unduly suffers a major financial burden that would likely delay or prevent a new component implementation. However, where economic impact is concerned, our economic analysis shows that ADS-B could be more controversial than other proposed system solutions. This situation is exacerbated by the fact that by the time ADS-B becomes a standard, the level of safety relative to runway incursions will be much greater than it is today. As a result, the economic stress on certain stakeholders may become difficult to justify for possibly small improvements in safety. This leaves open the question of whether a Backup System Configuration of ADS-B, with less than all aircraft equipped, might prove useful to the ground traffic control system. This possibility would allow more time to prove the safety enhancements provided by ADS-8 and more time for all aircraft owners to equip their aircraft with ADS-B.

Our systems approach is distinctive in that the solution we propose - use of statistical methods for safety assurance, data clustering analysis to decrease testing, and stakeholder economic analysis - results in a strategic way of managing the implementation of solutions aimed at improving the safety of the ground traffic control system. If our methodologies were followed, testing costs would be higher than currently planned for; however there would be a greater degree of assurance that the system being implemented would measurably reduce the current levels of incursion and collision rates. In a holistic sense, it is possible, by using our proposed method, that the FAA would realize greater cost savings over the long run by not implementing systems that fail to sufficiently decrease incursion and collision rates, or even inadvertently increase these rates.

*Recommendations*

The FAA should utilize statistical analysis to determine the appropriate amount of testing for rare events in the case of New System Configuration implementations. Since this requires a great deal of testing, we recommend implementing new solutions initially as Backup System Configurations in order to both achieve early safety improvements and to allow for the needed data collections prior to approving New System Configurations.

Statistical clustering analysis provides what could be a critical vehicle for expediting testing of new solutions. The FAA should establish an activity to explore this possibility with a team of aviation and statistical modeling experts who collaborate to analyze comprehensive runway incursion data sets. These data sets should provide detailed cause/effect information that permits higher fidelity models to be developed.

The FAA should explore the utility of an ADS-B system configuration for ground traffic control that doesn't require all aircraft to be equipped. For those members of the aviation community who would not be buying ADS-B for purposes other than runway incursion prevention, there would be a significant economic impact. It is not clear that by the time ADS-B is ready for implementation, that the benefits will justify the costs for those users. Research and development to lower avionics costs should also be investigated.

To ensure the completeness and quality of newly acquired data from the current system, a non-reprisal air traffic controller oriented reporting system should be instituted. Although it is possible that nearly every A or B incursion is reported, the majority of our industry contacts expressed concerns to the contrary. If under-reporting of runway incursions is taking place, then we would be testing our new systems to improve upon safety standards that could be set too high. In tum, this could unduly delay implementations that would have indeed improved safety. Moreover, this situation could possibly cause a good system to be undeservedly rejected. The improvement of the reporting system could be done at a relatively low cost when compared to the costs of the solutions under consideration.

Overall, our systems engineering perspective to reducing runway incursions provides an analytical approach for assuring the viability of future system solutions. While the current ground traffic control system needs improvement, it is very difficult to rigorously be confident about potential improvements. It is not enough to create new technology or come up with new procedures - those system components must be adequately evaluated in operational settings over substantial testing periods. Our proposed approaches, described in this report, provide a holistic systems analysis to: 1) hasten improving safety through introduction of new Backup System Configurations and 2) provide safety assurances about New System Configurations through suitable evaluations that are conducted while operating these solutions in a backup mode.

# FAA University Design Competition
# Contact Information (Appendix A)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**FAA University Design Competition**
**Description of the University (Appendix B)**

"The University of Virginia is made up of ten schools in Charlottesville, Virginia and is distinctive among institutions of higher education. Founded by Thomas Jefferson in 1819, the University sustains the ideal of developing, through education, leaders who are well-prepared to help shape the future of the nation. The University is public, while nourished by the strong support of its alumni. It is also selective; the students who come here have been chosen because they show the exceptional promise Jefferson envisioned" [46].

This project was undertaken by a group of 5 students, as part of a graduate class in the UVA Systems and Information Engineering Department. Professor Barry Horowitz, the SYS602-Systems Integration instructor, is a member of the National academy of Engineering and has extensive business and academic experience to include serving as President and CEO of the MITRE Corporation. During his time at MITRE he directly led the prototype development efforts that eventually led to TCAS. The student team members are a diverse group of individuals encompassing two fourth year undergraduate and three graduate students studying both systems and electrical engineering. In addition, our members bring unique perspectives and insight as we are multi-cultural, multi-national (United States, Serbia, Spain & Haiti) and have varied work experiences, to include representatives from the military and aviation communities.

FAA University Design Competition
Description of Non-university Partners (Appendix C)

(Not Applicable)

# FAA University Design Competition
# Evaluation of Educational Experience (Appendix E)

*Student Evaluation*

Our team members gained valuable educational experience m working on this paper through research activity, application of Systems Engineering methodologies, and the close team collaboration demanded to complete the paper.

From our interdisciplinary academic perspective, we have gained valuable knowledge on how to apply systems engineering methodology and touched on many different techniques - including statistical analysis, data mining, wide-ranging research activity, and systems integration. Our lectures from Professor Horowitz were relevant to Systems Management. This helped us realize early in the semester that the problem presented was a systems problem. We identified our added value to be the methodology and approach we could present through the application of Systems Engineering practices.

Through this assignment, every member has also gained indispensable knowledge on the current state of the runway incursion problem. The team members have explored and analyzed the current efforts currently being made to eradicate this problem, by the FAA and by other organizations. This problem that would have not otherwise been noticed by us has brought awareness and caution as members of society and as frequent fliers. The project has allowed us to be exposed to high-tech systems currently being developed and learn the priorities associated with their incorporation into a safety system.

- The UVA Student Team

*Faculty Evaluation*

There was great value added to this project by working on a real world problem with such relevance at present, even appearing in the cover page of the USA Today. This made us realize that there was a real chance to really make a difference in society.

Furthermore, the development of an abstract problem to a real feasible approach made us more aware of the environment, the situation, and made our work pragmatic.

Through the project, we brought together different techniques in systems engineering to solve one important problem. This is usually hard to find in an educational environment. The project was also developed in a small-class environment where I had the opportunity to know the students and to interact with them better than in a larger class.

- Dr. Barry M. Horowitz

# FAA University Design Competition
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# FAA University Design Competition
# Support Information (Appendix G)

**Appendix G.1: Standardized rates of A&B runway incursion: Support Material for Section IV**

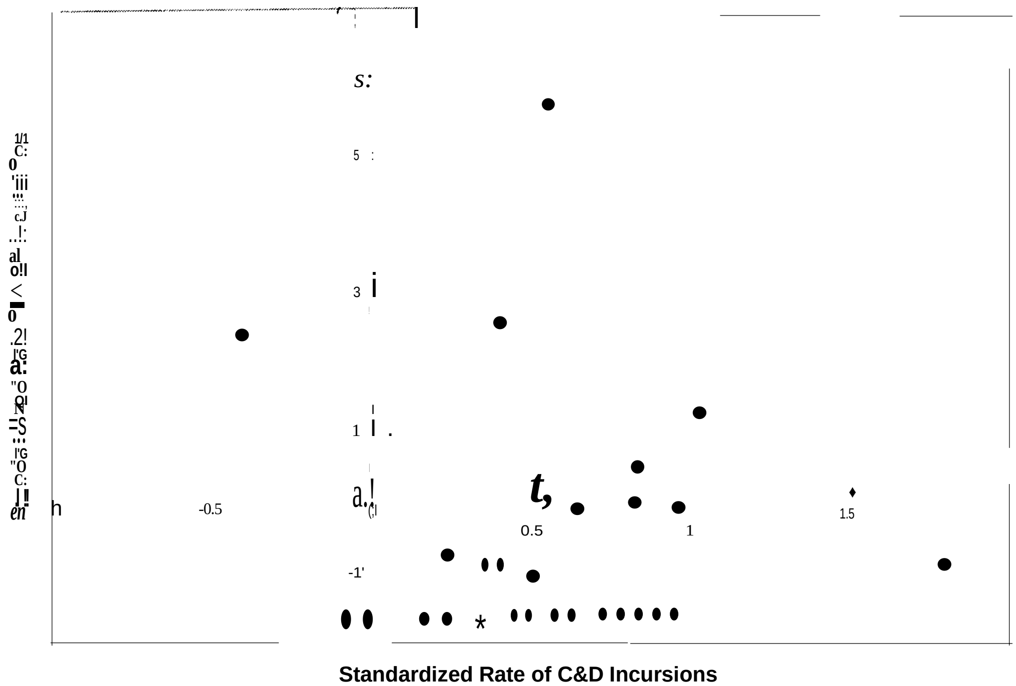


**Figure G.1.1: Standardized Rate of Type A&B Runway Incursions vs. C&D Incursions**

Figure G.1.1 depicts the standardized rate of A and B runway incursions at each airport plotted against the corresponding standardized rate of C & D incursions. The data was standardized so that the rate of A and B incursions could be accurately compared to the rate of C and D incursions.

The data for this calculation was taken from Appendix D of the (31]. To calculate the standardized rate of A and B incursions, we start by finding the rate of A and B incursions. For each airport we summed the total number of A and B incursions occurring over the four year period covered by the report. Next, we calculated the mean rate for all incursions (A-O which are given in the above mentioned reference) for each airport over the four year period. The mean rate of A and B incursions over the four year period is then calculated by dividing the sum of A and B incursions by the total number of incursions, then multiplied by the average rate of all incursions.

Having determined the rate of A and B incursions for each airport, we calculate the standardized rate of A and B runway incursions at each airport by subtracting the mean from the rate of A and B incursions and by then dividing by the standard deviation. This same process was then used to calculate the standardized rate of C and D incursions.

From Figure G.1.1, we cannot readily determine a strong correlation among the data points. Through calculations, we found the correlation coefficient of these two sets of data is .48, indicating no strong correlation between them.

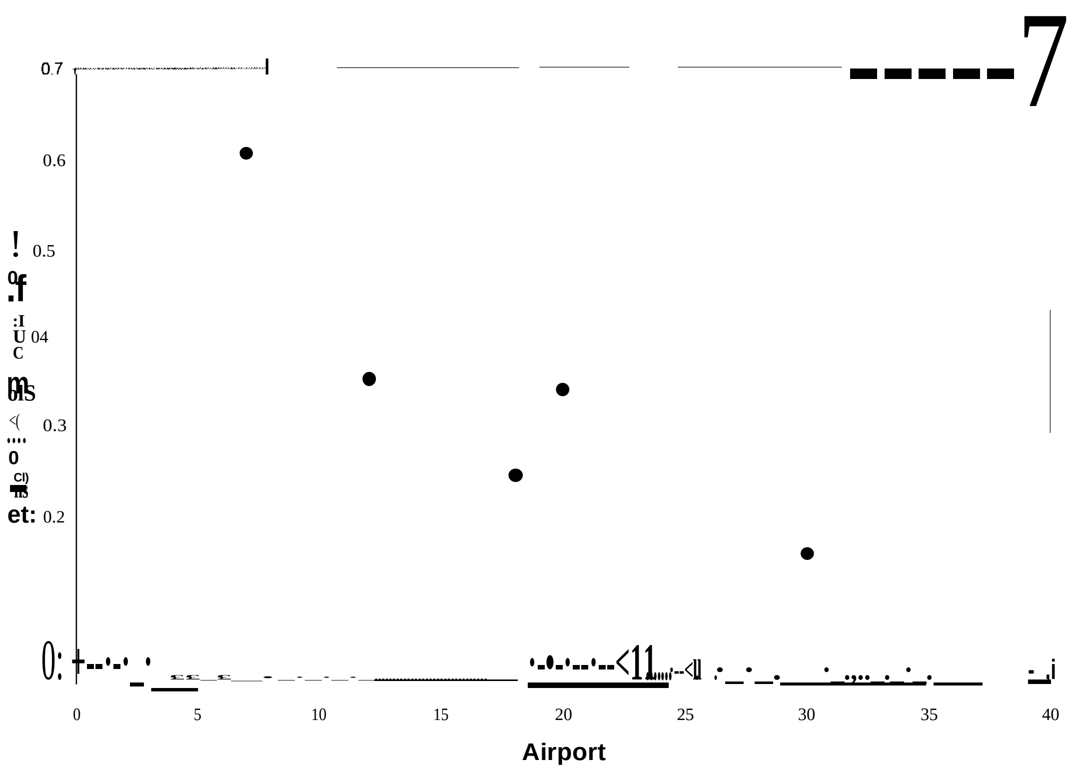


**Figure G.1.2: Rate of Type A&B Runway Incursions for OEP 35 airports**

Figure G.1.2 shows the average rate of A and B incursions for each airport. The values were calculated using the procedure described above. The purpose of this analysis is to identify outliers and or patterns that exist in the data. This idea is developed further in Appendix G.2.

| OEP35 | |
|---|---|
| 1 | ATL Hartsfield - Jackson Atlanta International Airport, Atlanta |
| 2 | BOS Boston - Logan International Airport, Boston |
| 3 | BWI Baltimore - Washington International Airport, Baltimore |
| 4 | CLE Cleveland Hopkins International Airport, Cleveland |
| 5 | CLT Charlotte - Douglas International Airport, Charlotte |
| 6 | CVG Cincinnati - Northern Kentucky International Airport, Covington / Cincinnati |
| 7 | DCA Ronald Reagan Washington National Airport, Washington |
| 8 | DEN Denver International Airport, Denver |
| 9 | DFW Dallas/ Fort Worth International Airport, Dallas |
| 10 | DTW Detroit Metropolitan Wayne County International Airport, Detroit |
| 11 | EWR Newark Liberty International Airport, Newark |
| 12 | FLL Fort Lauderdale - Hollywood International Airport, Fort Lauderdale |
| 13 | HNL Honolulu International Airport, Honolulu |
| 14 | IAD Washington Dulles International Airport, Sterling |
| 15 | IAH George Bush Intercontinental Airport, Houston |
| 16 | JFK John F. Kennedy International Airport, New York City |
| 17 | LAS McCarran International Airport, Las Vegas |
| 18 | LAX Los Angeles International Airport, Los Angeles |
| 19 | LGA LaGuardia Airport, New York City |
| 20 | MCO Orlando International Airport, Orlando |
| 21 | MOW Midway Airport, Chicago |
| 22 | MEM Memphis International Airport, Memphis |
| 23 | MIA Miami International Airport, Miami |
| 24 | MSP Minneapolis - St. Paul International Airport, Minneapolis |
| 25 | ORD O'Hare International Airport, Chicago |
| 26 | POX Portland International Airport, Portland |
| 27 | PHL Philadelphia International Airport, Philadelphia |
| 28 | PHX Phoenix - Sky Harbor International Airport, Phoenix |
| 29 | PIT Pittsburgh International Airport, Pittsburgh |
| 30 | SAN San Diego International Airport - Lindbergh Field, San Diego |
| 31 | SEA Seattle - Tacoma International Airport, Seattle |
| 32 | SFO San Francisco International Airport, San Francisco |
| 33 | SLC Salt Lake City International Airport, Salt Lake City |
| 34 | STL Lambert - St. Louis International Airport, St. Louis |
| 35 | TPA Tampa International Airport, Tampa |

**Table G.1: airport number for the OEP35**

## Appendix G. 2: Statistical Analysis: Support Material for Section V

Table G.2.1 shows the A and B runway incursion probability and average operations per month for each group of OEP airports. These values were calculated from information provided in the FAA 2005 Runway Safety Report. The analysis presented in Section V was based on these statistics.

| Operations Tier | Sum A&B's[1] | Total 0 perat1ons[2] | Probability[3] | Average Operations Per Year [4] | Per month [5] |
|---|---|---|---|---|---|
| Top | 6 | 7,419,289 | 8.08703E-07 | 927,411 | 77,284 |
| High | 22 | 24,447,373 | 8.99892E-07 | 509,320 | 42,443 |
| Medium | 8 | 15,752,329 | 5.07861E-07 | 328,174 | 27,348 |
| Low | 4 | 4,878,890 | 8.l 9859E-07 | 135,525 | 11,294 |

**Table G.2.1: OEP 35 statistics**

[1] Retrieved from the FAA Runway Safety Report August 2005, Appendix D (Table 4)
[2] Total operations were calculated using the rate of incursions from the FAA Runway Safety Report August 2005, Appendix D
[3] The probability for each tier of OEP 35 airports was calculated by dividing the number of A & B runway incursions by the total operations
[4] Average operations per year was calculated by obtaining the arithmetic mean of each tier
[5] Average operations per year divided by twelve months.

Tables G.2.2 and G.2.3 show the number of test operations required for each tier to assure a 95% and 75% likelihood that the system configuration being tested has a lower incursion rate than the historical system rate. The numbers of test operations were also converted into months by dividing the runs by the average monthly activity for each tier.

| | Top | | | | High | | | |
|---|---|---|---|---|---|---|---|---|
| | 95% | | 75% | | 95% | | 75% | |
| No. Rls Observed | Runs | Months | Runs | Months | Runs | Months | Runs | Months |
| 0 | 3700000 | 47.87521 | 1714216 | 22.18066 | 3328999 | 78.43393 | 1540514 | 36.29577 |
| 1 | 5866018 | 75.90185 | 3329573 | 43.08216 | 5271601 | 124.2032 | 2992173 | 70.49804 |
| 2 | 7785037 | 100.7325 | 4847770 | 62.72649 | 6996180 | 164.8357 | 4356530 | 102.6434 |
| 3 | 9587733 | 124.058 | 6318054 | 81.75085 | 8616208 | 203.0049 | 5677829 | 133.7743 |

**Table G.2.2: Test operations for the top and high operations tier airports.**

| | Medium | | | | Low | | | |
|---|---|---|---|---|---|---|---|---|
| | 95% | | 75% | | 95% | | 75% | |
| No. Rls Observed | Runs | Months | Runs | Months | Runs | Months | Runs | Months |
| 0 | 5898743 | 215.6936 | 2729677 | 99.81344 | 3653963 | 323.5391 | 1690891 | 149.7194 |
| 1 | 9340888 | 341.5591 | 5301916 | 193.87 | 5786207 | 512.3382 | 3284270 | 290.8048 |
| 2 | 12396703 | 453.2981 | 7719439 | 282.2692 | 7679135 | 679.9469 | 4781809 | 423.404 |
| 3 | 15267323 | 558.2653 | 10060684 | 367.8792 | 9457342 | 837.3978 | 6232088 | 551.8186 |

**Table G.2.3: Test operations for the medium and low operations tier airports.**

Table G.2.4 below shows the runway incursion and operations for the OEP 35 airports calculated from the reported rate of runway incursions.

| Airport Identifier and Name | A | B | C | D | Sum | Operations Per Year | Operations Over 4 Years | RATE |
|---|---|---|---|---|---|---|---|---|
| PDX Portland Intl. | 0 | 0 | 1 | 0 | | 67568 | 270270 | 0.37 |
| MCO Orlando Intl. | 0 | | 0 | 0 | | 75758 | 303030 | 0.33 |
| DCA Ronald Reagan Washington Nat. | 1 | 1 | 1 | | 4 | 81967 | 327869 | 1.22 |
| IAH George Bush Intercontinental | 0 | 0 | 0 | | 1 | 113636 | 454545 | 0.22 |
| TPA Tampa Intl. Airport | 0 | 0 | | | 2 | 125000 | 500000 | 0.4 |
| HNL Honolulu Intl. Airport | 0 | 0 | 2 | 1 | 3 | 156250 | 625000 | 0.48 |
| SAN San Diego Intl. - Lindbergh Field | 0 | | 1 | 4 | 6 | 157895 | 631579 | 0.95 |
| CLE Cleveland Hopkins Intl. Airport | 0 | 0 | 3 | 4 | 7 | 201923 | 807692 | 0.87 |
| MDW Chicago Midway Airport | 0 | 0 | 3 | 4 | 7 | 239726 | 958904 | 0.73 |
| SEA eatt{e • tacoma Intl. Airport. | 1 | 0 | 3 | 6 | 10 | **287356** | **1149425** | **0.87** |
| Pil,Pittsbur Intl. Airport | 0 | 0 | I | 2 | 3 | **288462** | **1153846** | 0.26 |
| FLL Fort Lauderdale - Hollywood Intl. | 1 | 3 | 2 | 4 | 10 | 291545 | **1166181** | **0.86** |
| ShC Salt Utl<e Ci **Intl. Ai Ort** | 0 | 0 | 4 | 5 | 9 | 293478 | 1173'913 | 0.77 |
| **IAO** | 0 | 0 | 4 | 3 | 7 | 305233 | **1220930** | **g.57** |
| BWI Baltimore - Washington Intl. | 0 | 1 | ·2 | 6 | 9 | 308219 | *121i311* | {m3 |
| JFK John F. Kennedy Intl. Airport | 0 | 0 | 0 | 7 | 7 | **315315** | 1261261 | (t56 |
| PHL Philadelphia Intl. Airport | 0 | I | 7 | 12 | **20** | 340136 | **1360544** | 1.47 |
| SFO San Francisco Intl. Airport | 0 | | 7 | 5 | 12 | | | 0.84 |
| DEN Denver Intl. Airport | 0 | | 4 | 8 | 12 | | | **0.80** |
| LGA LaGuardia Airport | 0 | 1 | 4 | 4 | 9 | 386266 | 1545064 | 0.58 |
| MEM Memphis Intl. Airport | 0 | 0 | 3 | 7 | 10 | 392159 | 1568627 | 0.64 |
| MIA Miami Intl. Airport | 1 | 1 | 4 | 6 | 12 | 425532 | 1702128 | 0.71 |
| EWR Newark Liberty Intl. Airport | 2 | 0 | 2 | 9 | 13 | 429043 | 1716172 | 0.76 |
| STL Lambert - St. Louis Intl. Airport | 0 | 2 | 9 | 13 | 24 | 443623 | 1774492 | 1.35 |
| BOS Boston - Logan Intl. Airport | 0 | 1 | 6 | 3 | 10 | 452489 | 1809955 | 0.55 |
| CLT Charlotte - Douglas Intl. Airport | 0 | 0 | 3 | 6 | 9 | 456858 | 1827411 | 0.49 |
| CVG Cincinnati - Northern Kentucky Intl. | 0 | 0 | 8 | 5 | 13 | 492424 | 1969697 | 0.66 |
| MSP Minneapolis - St. Paul Intl. Airport | 0 | 0 | 6 | 7 | 13 | 511811 | 2047244 | 0.64 |
| LAS McCarran Intl. Airport | 0 | 1 | 4 | 8 | 13 | 517928 | 2071713 | 0.63 |
| DTW Detroit Metro. Wayne County Intl. | 0 | 3 | 4 | 9 | 16 | 544218 | 2176871 | 0.74 |
| PHX Phoenix - Sky Harbor Intl. Airport | 1 | 1 | 9 | 12 | 23 | 603675 | 2414698 | 0.95 |
| DFW Dallas / Fort Worth Intl. Airport | 1 | 2 | 5 | 11 | 19 | 603814 | 2415254 | 0.79 |
| LAX Los Angeles Intl. Airport | 0 | 6 | 8 | 15 | 29 | 630435 | 2521739 | 1.15 |
| ATL Hartsfield - Jackson Atlanta Intl. | 2 | 1 | 6 | 9 | 18 | 918367 | 3673469 | 0.49 |
| ORD O'Hare Intl. Airport | 2 | 1 | 18 | 7 | 28 | 936455 | 3745819 | 0.75 |

**Table G.2.4: OEP 35 airports statistics ordered by volume of operations [31)**

## Appendix G.3: Airport Clustering Analysis: Support Material for Section V

Cluster Analysis is a technique for data segmentation. This technique has several different goals. These goals all relate to grouping or segmenting a set of observations into subsets or clusters. These grouping are made such that the observations within each cluster are more closely related to one another than they are to observations in different clusters. The most important idea in cluster analysis is the degree of similarity between the observations being grouped [47].

Hierarchical clustering treats each observation as a single cluster, and then successively merges them clusters until all the observations have been grouped into one big cluster. The hierarchical clustering will be visualized as a tree [48]. A dendrogram is a tree diagram that is used to illustrate the organization of the clusters [49].

*Distance measures:* There is more than one way to measure distances in the cluster matrix. There are distances that are Euclidean, based on the length of the path connecting two points, and there are other distances based on similarity, for example the Manhattan distance.

We chose to use the Euclidian distance since it is the most common way to measure the distance between two distinct points. We square the standard Euclidean distance in order to place progressively greater weight on objects that are further apart. This distance[50] is computed as:

$$\text{Distance}\,(x,y) = \{\textstyle\sum_i (x_i - y_i)^2\}^{1/2}$$

*Clustering rules:* The most common clustering rules are complete-link, single-link and average link clustering. We chose diagrams with complete-link clustering since it yielded the most distinct set of cluster out in our analysis including all the variables considered. We kept the complete link clustering for all subsequent examples in the paper.

In complete-link (or complete linkage) hierarchical clustering, we merge in each step the two clusters whose combination has the smallest maximum pair wise distance.

*Modeling with S-PLUS:* We use the statistical package S-PLUS to perform the cluster analysis and come up with our dendrograms. This program performs a hierarchical clustering on a distance or similarity structure. At each stage the two similar clusters are combined to form one bigger cluster. Initially each cluster contains a single point [51].

*Dendrograms:* The resulting dendrograms from our clustering technique are as shown in Section V. To identify the airports, see the following list of OEP 35 airports with their corresponding number.

*Analysis:* When S-PLUS provides the dendrogram including all of the considered variables, it produced the same result as the dendrogram based on only the number of operations. The high magnitude of the variable number of operations strongly affects the distances of the similarities and does not leave room for the other variables to be accounted for. To count all variables evenly, we standardize the variables by subtracting the variable's mean value from each data column and dividing it by the variable's mean absolute deviation.

## Appendix G.4: System Component Cost Calculations: Support Material for Section VI

*Runway Markings Cost Determination*

Based on a research done by MITRE Corp. [52] within an airport surface marking project, they determined different factors that come into play when assessing the average unit price for each enhanced runway holding position marking.

There are several different types of paint that can be used for these enhanced markings. The price between the different types of paint varies greatly. In the MITRE assessment it was determined that the in-house maintenance installation pricing will generally be lower than commercially contracted services mainly because contractors will add a profit margin ranging from IO to 40%. Taking into account these factors, this table provides a cost comparison between the three marking proposals at PVD that are painted at all taxiway runway intersections with the two marking proposals on a single runway at BOS. The costs at PVD included removal of old markings.

| Airr1orl | lnstullation \lethod | \11mhe1· of RIIIIWfl)"!I | Numl r of Holdline | t:nhan.-ed \larl..inia '\| llt' | Bt>ad ·l'nir | SiLI"Of Inscription (infl.!m) | Lalro1· 1111d latt-rial Total Cost (without stencil) | Estimated l'ost 1 r Ru11wa) Holding Po ition |
|---|---|---|---|---|---|---|---|---|
| **PVD** | in-house | | f() | - markin | I | 9.:3 | S!S O,W, | $()<.() |
| **BOS** | Nnuractcd | I | lb | 2 marb. nµ\ | I | 12:3 {17 | SI I.MD | $72 |

**Table G.4.1: PVD and BOS Markings' Cost Comparison**

For our cluster analysis, we had collected data on the number of crossing taxiways and the number of terminating taxiways at these airports. To determine the number of runway holding position, we multiplied the number of crossing taxiways by 2 and added the number of terminating taxiways to the later. We used the average of the estimated cost per runway holding position for PVD and BOS to do our calculations for all the OEP 35 airports.

We assumed that all the runways of these airports are repainted every year. The total price for enhanced markings at all the OEP is $1,417,887.50. The average cost per airport at the OEP 35 is$ 40,511.

*Runway Status Lights Cost Determination*

To calculate the cost of the Runway Status Lights (RWSL) runway incursion prevention systems, we needed to make several assumptions. A large number of our numerical results were obtained from a presentation by Wallace Ferrar of MITRE, who provided us with data on the cost of implementing a RWSL system on a per runway basis [38)

Using this data, we assumed that we were working with an average OEP 35 airport with an already installed ASDE-X radar system. Averaging the number of annual operations at each of the OEP 35 airports, the number of runways at each airport and the number of runway/taxiway crossings occur at each one, we were able to derive assumptions for a representative airport on which we based our economic calculations. Furthermore, we assumed that the labor costs of installations, training and maintenance were accounted for in the MITRE estimate. The worksheet below presents the steps and results of the calculations described above.

**Worksheet G.4.1: Cost breakdown for an average OEP 35 airport RWSL system implementation**

| | | |
|---|---|---|
| **Cost per Runway (assuming avg of 8 intersections)** | $802,100 | per runway |
| | $100,000 | per intersection |
| ASSUME THAT NEITHER PILOTS NOR AIR TRAFFIC CONTROLLERS NEED EXTRA TRAINING (outside of their current mandatory training) | | [38) |
| *Labor costs of installation have been included | | |
| *Assume Additional Maintenance costs of Labor are covered in the above analysis | | |

| **Aircraft Speed and Distanc**elte **alculations** | | | |
|---|---|---|---|
| airliner lands at about | 150 | mph | [53] |
| airliner takes off | 150 | mph | [54] |
| | 792000 | ft/hr | |
| | 220 | ft/sec | |

approx length of used runway 8,000.00 ft [55]
approx range per intersection 800.00 ft
ASSUME: total deceleration/acceleration of airplane over given length of runway

**Length of Light Operation**

| | | |
|---|---|---|
| ver•e,t ngth ... tit1ie per intersection, per operation | 36.36 | seconds |
| ON ti e per year per light | 13,090,909 | sec |
| | 3,636.36 | hrs |
| 'rotaion time per year (sum of all bulbs) | 58,181.82 | hrs |

**Electricity Costs of Operation**

| | | | | | |
|---|---|---|---|---|---|
| ASSUME | 100 | W per bulb | [56] | 5,818.18 | kW*hrs |
| Price of electricity is | | [57] | | 0.07 | per kW*hr |
| **Annual Cost of Electricity** | | | | **$407.27** | **$/air** |

**Fixed Costs (Installation, materials, including labor)**

ASSUME: 10 intersections per runway (avg. value from OEP 35 data)
40 intersections per airport
4 runways per airport
8 lights per status line (one sided intersection)
8 lights per lead on line *(assume these two kinds of lights are the same)*

**Light Installation (Lead on Lights)**

| | | | | |
|---|---|---|---|---|
| ASSUME | 8 light lead on lights per line | 95,240 | | $3,809,600.00 |
| Initial Cost of Lights | $95,240 | per intersection | | per airport |
| (assuming average of 8 intersections per airport) | | | | $100,000 |
| Cost per Runway | $802,100 | per runway | | per intersection |
| | | | | $4,000,000.00 |
| Initial System and Installation | 100,000 | per intersection | | per airport |
| | | | TOTAL = | $7,809,600.00 |

**Operational Costs (other)**

| | | |
|---|---|---|
| # oflid,\ts p'er interaection | 16 | per intersection (estimated) |
| # oft)peta,ti.ons•tier hr | 50 | |
| # Oi:!QP rationsper day (20hrs) | l,000 | operations/day |
| per addh year(3'1lll!J-Ys) | 360,000 | |
| # ofrun ajS per operation | 1 | runway/operation |
| # pf i,teraecti tts per op | 10 | intersections/operation |
| #ti htper operation | 160 | lights/operation |

**Maintenance and Lifecycle Costs**

| | | | |
|---|---|---|---|
| Average Lifetime of a bulb | 1000 | Hrs [56] | I 000 hrs/bulb |
| Annual intersection replacements | 3.64 | | |
| Annual bulb replacements | 2,327.27 | per airport | 3600000 seconds/bulb |
| Replacement Cost | $300.00 | per 8 lights | [38] |
| | $ 37.50 | per light | |
| Annual Light Replacement Cost | | $87,272.73 | per airport |
| | | $2,181.82 per intersectio | $87,272.73 per airport |

**Opportunity Costs:** Cost of Closing a Runway for one day-avg $ 120,000.00

ASSUME: all work is done at night & runway closure will be negligible

***However inconveniences caused by night work are estimated at 20%[58]

| | | |
|---|---|---|
| inconvenience factor | 20.00% | |
| adjusted initial installation cost | $9,371,520 | per airport |

**:OMBINING ALLOFTHE NFORMA'T'ION**

A ;$ : pdiscount factors or inflation 10 year period

**1otalcolt.•of system over l@years** | $10,24s,320 **pera:it·port** |

*Airport Surface Detection Equipment, Model X (ASDE-X) System Cost Calculation*

The ASDE-X system total lifecycle cost of $13,000,000 per year for a ten year period per average airport was based on a Federal Aviation Administration Summary Information and Justification request for federal funding from 2006 [59]. The cumulative total budgetary resource for previous years through 2008 is $439,117,000. Assuming this cost is spread equally among the 35 airports where it will be installed, the total lifecycle cost per airport is $12,546,000. This result was rounded up to $13,000,000 to serve as a rough order of magnitude system cost. Further corroboration of this result was found in an article reporting on meeting minutes from the House Aviation Subcommittee [60].

*Automatic Dependent Surveillance-Broadcast, (ADS-BJ System Cost Calculation*

There are three ways that the ADS-B system can be used with respect to reducing runway incursions. The first is that it can be used within the framework of the current ATC system by providing controllers with improved surveillance information. The second would involve pilots using the system as a check to the instructions given to them by ATC via a situation awareness display in the cockpit. The third is for pilots to provide their own separation via information provided in the cockpit.

We are only considering the second of these cases for the economic analysis. We assume that the costs of ADS-8 avionics are totally allocated to improvements relative to runway incursions. Recognizing that there are many values that will be provided by ADS-B, this approach provides an upper bound for allocating ADS-B avionics costs. However, as the FAA moves forward with the NAS implementation plan, they should ensure the special ground system ADS-B costs related to runway incursion safety reductions is included. Because we are looking at having a display in the cockpit to provide a check on the directions given by ATC, all aircraft would have to have an "ADS-B in" system. Our avionics costs were derived from data provided in [61].

Prices for equipping an aircraft with "ADS-B in" are dependent on the type of aircraft and the amount of equipment initially present in the aircraft [61]. We use these results as the basis for our ADS-B cost analysis.

General Aviation:

No equipment CDTI: $12,500 - $282,100

GPS CDTI: $5,000- $218,100

Air Transport:

No equipment CDTI: $178,800 - $564,300

GPS CDTI: $115,600-$436,200

CDTI: Cockpit Display of Traffic Information

*Final Approach Runway Occupancy Signal, FAROS System Cost Calculation*

The estimated average installation cost of a FAROS system for an OEP 35 airport is $883,000. Based on the data presented in Table 1 below, our analysis shows that FAROS installations can range from $2 million to $240,000, depending on the number of activation zones the airport has or wants to cover with FAROS [62].

**Final Approach Runway Occupancy Signal (FAROS)**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Price per set of PAPI lights** | | | | | $ | 40,000.00 |
| | | | | | | [62] |
| **In-pavement sensor loop per leg** | | | | | $ | 5,000.00 |
| **Wiring and installation** | | | | | $ | 5,000.00 |
| **Total Price Of Loop Sensors** | | | | | $ | 15,000.00 |
| **TOTAL** | $ | 30,915,000.00 | $ | 78.29 | $ | 0.78 |
| **Min** | $ | 240,000.00 | $ | 0.46 | $ | 0.00 |
| **Max** | $ | 2,035,000.00 | $ | 7.64 | $ | 0.08 |
| **Aveg** | $ | 883,285.71 | $ | 2.24 | $ | 0.02 |

## Appendix G.5: Stakeholder Economic Analysis Calculations: Support Material for Section IV

Figures for all system components (ASDE-X, ADS-B, FAROS, RWSL and paint) were taken from Appendix G.4. For annual per passenger calculations, the total system cost was divided by the total number of commercial passengers per year at the OEP 35 airports and then multiplied by 35 to account for all of the OEP 35 airports [63, 64]. The only exception to this method was for the per passenger result for ADS-B based systems. This was calculated by taking the average annual cost to a commercial aircraft [61] times the total number of commercial aircraft operating at OEP 35 airports (estimated) plus the approximate cost for infrastructure at an airport [65] times 35 to account for all OEP 35 airports. This intermediate result is then divided by the total number of passengers to compute ADS-B per passenger annual cost.

For the commercial airline ASDE-X, FAROS, RWSL and paint costs, we assume that the expense to airports would be recouped through landing fees. These landing fees are based on weight of the aircraft [45]. Commercial aircraft take up the greatest portion of traffic and weight of aircraft at OEP 35 Airports. Therefore we weighted commercial aviation as 100% of the total fee that the airport bears, divided by the product of the total number of commercial flights at OEP 35 airports [66]. We then divided this number by 35, to get a per flight cost. For the ADS-B commercial airline cost, the range is based on the possible need for a concurrent OPS installation, as well as a variety of other variances. Each per flight estimate was calculated by taking the airport's cost divided by the OEP 35 commercial traffic operations average, plus the ADS-B per aircraft estimate divided by the average number of flights at an OEP 35 airport. The ADS-B per aircraft annual cost estimate is calculated by taking the total cost for one system aboard one aircraft [61] and dividing by IO to spread the cost over a ten year period.

The general aviation figures are computed in the same manner as the commercial airlines using the appropriate cost for general aviation ADS-B cost per aircraft [61] for that category.

The Average OEP35 Airport costs are determined by taking the total annual system component cost (ground system infrastructure cost for ADS-B) [65] and multiplying by a factor of .25 to estimate the airport's shared cost with the FAA at these major airports. The percentages in this row indicate the percent of the annual airport operating budget for each system component, based on using Los Angeles International Airport's annual budget as a baseline [67].