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Health Monitoring System Technology Assessments – Cost Benefits Analysis

Renee M. Kent and Dennis A. Murphy
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ABSTRACT

The subject of sensor-based structural health monitoring is very diverse and encompasses a wide range of activities including initiatives and innovations involving the development of advanced sensor, signal processing, data analysis, and actuation and control technologies. In addition, it embraces the consideration of the availability of low-cost, high-quality contributing technologies, computational utilities, and hardware and software resources that enable the operational realization of robust health monitoring technologies.

The evolution of these dynamic and robust technologies has been the result of the disciplined application of systems engineering practices and techniques. It has been stimulated and facilitated by a focused appreciation within the civil, aerospace, and mechanical engineering communities of the tremendous capabilities associated with advanced materials, sensing and instrumentation technologies, micromechanics, process control and actuation, and data and signal processing. However, operational implementation of the technology requires that the technology base be economically viable, as well.

This report presents a detailed analysis of the cost benefit and other logistics and operational considerations associated with the implementation and utilization of sensor-based technologies for use in aerospace structure health monitoring. The scope of this report has been tailored to provide an assessment of the economic impact, from an end-user perspective, of implementing health monitoring technologies on three critical structures. Specifically, it focuses on evaluating the cost benefit impact of maintaining and supporting these structures with and without health monitoring capability.

ABBREVATIONS AND ACRONYM

AC	Acquisition Cost
AD	Airworthiness Directive
ALI	Airworthiness limitation instructions
ASHMS	Aircraft Structural Health Monitoring System
CASA	Cost Analysis Strategy Assessment
CBA	Cost Benefit Analysis
CER	Cost Estimating Relationship
CES	Cost Element Structure
CMR	Certification Maintenance Requirement
DoD	Department of Defense
ED	Environmental Deterioration
FAA	Federal Aviation Administration
FD	Fatigue Damage
LASHM	Life Cycle Aircraft Structure Health Management
LCC	Life-cycle Cost
LCCM	LCC Model
LDT	Logistics Down Time
LLM	Life Limits Management
Mct	Mean Corrective Time
MDT	Mean Downtime
MEMs	Microelectromechanical Systems
MFHBM	Mean Flight Hours Between Maintenance
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTSM	Mean Time for Scheduled Maintenance
MTTR	Mean Time To Repair
NDE/I	Non-destructive Evaluation and Inspection
NLT	Not-later-than
O&D	Operations and Destination
O&M	Operations and Maintenance
O&S	Operations and Support

ABBREVATIONS AND ACRONYM (continued)

PSE	Principal Structural Elements
PZT	Piezoelectric
R&D	Research and Development
R&M	Reliability and Maintainability
RDT&E	
ROI	Return on Investment
SE	Support Equipment
SSI	Structurally Significant Items
T&E	Test and Evaluation
TAT	Turnaround Time
TE	Test Equipment
TRACE	Total Resource and Cost Evaluation

CONTENTS

Page

CONTENTS (continued)

Page

SECTION ONE

INTRODUCTION AND OVERVIEW

1.1 BACKGROUND

Recent initiatives by the National Aeronautics and Space Administration (NASA) are focused on identifying and evaluating aircraft structural health monitoring system (ASHMS) technologies intended to enhance the operational safety of commercial aircraft by providing:

- Real-time or near real-time characterization of structural condition and integrity.
- Improved processes and procedures for aircraft life-cycle management and maintenance.
- Feedback of real-time dynamic flight information related to aircraft structural integrity for the opportunity for flight control and recovery.
- Capabilities for reading, translating, processing, and analyzing data generated by embedded sensor, instrumentation, and control systems.

However, in order for the ASHMS to be operationally viable, it must also be cost effective. This means that economic factors must be appropriately balanced against the technical, operational, and support benefits that may be associated with the use of the advanced ASHMS technology. The key is to answer the question:

"Are the expected benefits worth the initial and recurring investments?"

This report presents the framework for answering that question.

1.2 PURPOSE AND OBJECTIVES

The purpose of the ASHMS Cost Benefit Analysis (CBA) is to perform an objective and disciplined analysis, in terms of cost and other measures, of the impact for large commercial air carriers of endowing existing aircraft structures with state-of-the-art ASHMS technologies. This analysis can then be used to:

- Identify economic, engineering, operational, and logistics considerations that are critical for effective decision-making relative to technology development, insertion, and migration opportunities.

- Provide a decision basis for balancing the relevant investment cost against these considerations.

- Identify where cost savings and positive return on investment can be realized.

- Encourage and facilitate up-front user input and involvement in planning and implementation.

- Minimize the impact, cost, and risk of future implementation and integration.

- Capitalize on cost-effective technology insertion and process enhancement opportunities.

To this end, the CBA addresses the hypothesis that sufficient economic, engineering, operational, and logistics benefits may be realized by introducing sensor-based ASHMS technologies into selected aircraft structures to make the proposed initiative cost-effective. Specifically, this study addresses:

- The return on investment (ROI) relative to estimated development, acquisition, integration, and certification cost of the ASHMS.

- The relevant expected life-cycle cost (LCC) of providing logistics support for aircraft structures without an ASHMS and with an ASHMS.

- Other qualitative (i.e., noneconomic) benefits and considerations (e.g., safety, operational capability, environmental impact, and opportunities for life extension, maintenance streamlining, and technology insertion) that may influence decisions regarding the development and implementation of ASHMS.

1.3 SCOPE

Extensive research and analysis are required to determine the benefits associated with developing and implementing a viable ASHMS capability. Consequently, in order to contain the scope and cost of the study, this analysis is limited to assessing the life-cycle cost and benefits, and logistics support cost and benefits of only three structural components. These components are the vertical stabilizer, a trailing edge structure (e.g. flap or aileron), and the engine mount. (Note that any impact on operational revenue to the commercial air carriers is considered to be outside the scope of the current CBA).

1.4 CONCEPTUAL APPROACH

The fundamental conceptual approach for performing this CBA consists of two parts. First, we compare the estimated LCC of maintaining and supporting airframe structures without an ASHMS capability (commonly called the logistics support cost) to the estimated LCC of maintaining and supporting these structures after an ASHMS has been incorporated. The difference between the logistics support cost of these alternatives provides the economic basis for characterizing the estimated cost benefits. Then, the second part of the approach involves identifying other factors and considerations that may influence the decision whether to incorporate ASHMS, from a non-economic basis. At the top-level, the overall approach includes:

- Estimating relevant cost for the reference and alternative systems (i.e., the structural components without and with an ASHMS)
- Assessing LCC difference between alternative and reference systems
- Determining return on investment and the associated break-even point.
- Assessing qualitative considerations

1.5 DEFINITIONS

The following definitions were used in performing and documenting this ASHMS CBA.

- ***Reference system*** - an existing system with an equivalent or similar use to a proposed alternative system against which it is compared. For example, in this CBA, the reference systems are the existing structural components of interest.
- ***Alternative system*** **–** a system that has a use equivalent or similar to the reference but includes any proposed technology upgrades. For example, in this case, the alternative systems are the same structural components as the reference systems but having ASHMS capability.
- ***Relevant cost*** - a cost element that impacts a decision that is based on economic factors. For this CBA, the relevant cost elements are those cost drivers for which significant differences exist between a reference system and the corresponding alternative system. These cost elements will have the greatest impact on the economic considerations associated with the implementation of an ASHMS .
- ***Life-cycle cost*** (LCC) - the total cost associated with the acquisition and ownership of the system over its full life, from design conception until its operational retirement and disposal. LCC is made up of research, development, test, and evaluation (RDT&E) cost, acquisition cost, operations and support (O&S) cost; and disposal

cost. Typically, over a system's life, O&S cost exceeds both development and initial investment cost. Since for the purposes of this study, we are only considering relevant cost, LCC is used in this document refer to the LCC associated with maintenance and support that are expected to change as a result of acquiring, implementing, and using ASHMS.

- ***Research, development, test, and evaluation cost*** (RDT&E): the cost associated with the research and development (R&D) and test and evaluation (T&E) of system hardware and software. Specifically, it includes the cost for performing conceptual research; technical feasibility studies and trade-off analyses; engineering design, assessment, simulation, and modeling; prototype development, fabrication, and test; system test and evaluation; and preparation of engineering data and associated technical documentation.

- ***Acquisition cost*** (AC): also referred to as ***investment cost***, this is the total non-recurring and recurring cost associated with producing, procuring, and deploying system hardware and software, system-specific SE and test equipment (TE); initial training; technical data; software development; facilities construction and modification; inventory introduction; warranties; and contractor support. For the purposes of this CBA, the AC of interest refers to the acquisition of ASHMS.

- ***Operations and support cost*** (O&S): the cost associated with operating, maintaining, and supporting a fielded system. This cost includes maintenance labor, consumable and repairable materials, support equipment (SE) maintenance, facilities, and other sustaining and recurring investment. O&S cost is incurred both in preparation for and after a system's fielding; it continues through the end of the system's useful life.

- ***Disposal cost***: the cost associated with deactivating, retiring, demilitarizing, or disposing of a system at the end of its useful life, minus any salvage value. Since this cost typically represents only a small fraction of a system's LCC, it is usually excluded from most LCC analyses, as they were in this study.

- ***Logistics support cost*** (LSC) - the total recurring cost associated with maintaining and supporting the reference or alternative system over the system's life cycle. Since for the purposes of this CBA, we will be considering only relevant cost, the LSC referred to in this document describes relevant LSC.

- ***Return on investment*** (ROI) - the total LCC savings realized relative to the acquisition cost and resulting from of the initial investment. For this CBA, the ROI is computed by subtracting the AC of ASHMS from the LCC savings, if any, resulting from implementing an ASHMS. The ROI annualized over the life-cycle of the aircraft is the ***annual ROI***

- ***Annual Percentage Rate of ROI –*** the annual ROI relative to the AC. Annual percentage rate of ROI is computed by dividing the annual ROI by the AC.

- ***Break-even point* –** the time required to recoup the initial investment made for acquiring and implementing the alternative technology. Break-even point is computed by dividing the total acquisition cost by the annual return on investment (annualized over the life cycle of the aircraft).

1.6 REPORT OVERVIEW

A brief background of the technology basis for an ASHMS is provided in Section 2. The detailed CBA approach is described in Section 3. As part of Section 3, we have provided some tutorial information about general cost analysis approaches as well as the application to this study, in particular. This is primarily for any readers who may not be intimately familiar with CBAs. Section 4 describes the groundrules and assumptions used in performing the CBA. The cost analysis and results are provided in Sections 5 and 6, respectively. Other engineering, operational, and logistics considerations, including several additional benefits associated with the use of an ASHMS, are discussed in Section 7. In Section 8, we present the overall CBA conclusions.

SECTION TWO

BACKGROUND FOR AIRCRAFT STRUCTURAL HEALTH MONITORING

2.1 OVERVIEW

ASHMS technologies, composed of a network of sensors, and data interpretation and management equipment, are configured to read and translate information regarding the structural integrity of airframes. The emergence of highly reliable sensor, signal processing, and data analysis technologies offers the technical feasibility of integrating such advanced sensor-based ASHMS networks within airframe structural systems. Such structures can offer economically viable life-cycle benefits due to the potential for improving operational capability, reducing maintenance downtime and resources consumption, increasing safety, and enhancing component durability, reliability, reparability, and survivability. These benefits are achievable because of the technological opportunities associated with dynamic in-service monitoring of parameters such as internal and external strain, pressure, temperature, fracture, degradation, and fatigue dynamics of aerospace structures and components.

2.2 OPERATIONAL NEED

The performance and behavior characteristics of airframe structures can be affected by degradation resulting from sustained use within flight envelopes, as well as from exposure to severe environmental conditions or damage resulting, for example, from impact, loading, abrasion, operator abuse, or neglect. These factors for primary load-bearing structures can have serious consequences relative to safety, cost, and operational capability. Consequently, the timely and accurate detection, characterization, and monitoring of structural cracking, corrosion, delamination, material degradation, and other flaws, defects, or damage are a major concern in the operational environment.

Fail-safe structural design and engineering techniques are used to mitigate the safety risk from the presence of specific inherent defects and flaws within most structural components so that the likelihood of inherent defects and flaws leading to catastrophic failure is reduced. However, degradation of and damage to structural components do occur during operational utilization and, if left uncorrected, can propagate and increase the risk of a catastrophic structural failure. Consequently, acquiring insight into the nature, extent, and distribution of defects, flaws, damage, and degradation incurred in a structure is critical to:

- Facilitating structural integrity management for the component for ensuring flightworthiness and improved safety.

- Preserving or extending, as appropriate, the component's service life.

- Understanding and optimizing the component's performance.

Currently, the primary emphasis for structural "health monitoring" is on using traditional nondestructive evaluation and inspection (NDE/I) methods for detecting and characterizing the initiation and progression of structural defects, flaws, damage, and degradation. In short, a rigorous schedule of periodic NDE/I and repair actions is directed by the aircraft manufacturer through published Services Bulletins (SBs), and by the Federal Aviation Administration (FAA) through the issuance of Airworthiness Directives (ADs). These SBs and ADs are guided by indications and reports of structural anomalies that are considered to be safety risks if left uncorrected. The successful utilization of these methods for structural applications demands that reliable, efficient, and cost-effective NDE/I techniques, procedures, and equipment be used.

However, current NDE/I methodologies are often time-consuming and expensive; this is because they usually involve the use of complex (and costly) NDE/I support equipment or partial disassembly of the structure. In addition, the reliability of these methodologies depend, to a great extent, upon the type and condition of support equipment used, the techniques and environment under which this equipment is used, and the capabilities and experience of the inspectors and technicians. Consequently, there has been increased interest in recent years in investigating the economic, engineering, operational, and logistics benefits associated with integrating aircraft structural health monitoring system (ASHMS) technologies into advanced aerospace structures.

SECTION THREE

THE COST BENEFIT ANALYSIS APPROACH

3.1 BACKGROUND

The CBA analysis approach used by ARINC is based on proven systems engineering and LCC analysis principles. It focuses on utilizing capabilities and methodologies that allow realism with the flexibility and adaptability to deal with:

- ASHMS technologies that may not be fully mature (from an engineering or implementation perspective).
- Limitations in data availability, reliability, or completeness.
- Uncertainty and variability relative to operational and logistics concepts, policies, practices, and procedures used by the air carriers.

3.2 HYPOTHESIS

As previously discussed, ARINC's focus in accomplishing this CBA was to address the hypothesis that sufficient economic, engineering, operational, and logistics benefits may be realized by introducing sensor-based ASHMS technologies into selected aircraft structures to make the proposed initiative cost effective from a return on investment perspective. Although this hypothesis states that the overall LCC will decrease with an ASHMS system, it should be noted that individual cost elements may either increase (e.g., technical data, facilities, and engineering changes) or decrease (e.g., maintenance labor and materials) over time, thereby impacting the magnitude and timing of the ROI. For example:

- Initially, direct repair cost for the structural components with ASHMS may increase because of the added complexity of the structures with embedded ASHMS components.
- Eventually, labor and material cost associated with structural repairs should decrease, because repairs are expected to be less extensive, complex, and costly due to early defect and degradation detection.
- Eventually, maintenance support cost (e.g., support equipment and NDE/NDI) are expected to decrease because of a greater reliance on less costly on-condition or

condition-based maintenance (as discussed in Section 7.0) as opposed to periodic (scheduled) teardown and inspection.

- Cost associated with structural component condemnation actions may decrease because uncorrected defects or degradation requiring such action will be greatly reduced.

In addition to any direct LCC benefits, implementation of an operationally viable ASHMS may:

- Increase aircraft operational availability, with the opportunity for increased revenue (which it is outside the scope of this study to project). This improvement will be driven by such things as:

  – The reduced mean downtime (MDT) associated with the decreased dependence on scheduled maintenance.

  – Decreased component mean time to repair (MTTR).

  – Faster aircraft maintenance turn-around-time (TAT).

- Reduce accident rates.

- Provide opportunities for maintenance streamlining and aircraft life extension.

3.3 LIFE-CYCLE COST (LCC) ANALYSIS PROCESS

The LCC analysis process used by ARINC in performing the CBA involved four fundamental activities:

- Development of the LCC analysis approach

- Achievement of customer (NASA Langley Research Center [LaRC]) and user (the commercial air carriers) concurrence with the approach

- Preparation of the LSC estimates

- Presentation of the results

We will start by describing the development of the LCC analysis approach. Then, the next subsection of the report will describe how ARINC developed the LCC analysis approach and obtained concurrence from representatives from NASA and several commercial air carriers. In subsequent subsections, we present the steps we took to prepare the LCC estimates (reference and alternative systems), including the selection of the cost estimating methodology and detailed data collection and analysis. In Section 4, we present the detailed Groundrules and Assumptions for this analysis. In Section 5, we present a discussion of the cost analysis, and in Section 6, the results are described. Finally, Section7 provides a non-economic perspective of factors and other considerations that might impact the implementation and utilization of the ASHMS technology.

3.3.1 Development of LCC Analysis Approach

In the development of the LCC analysis approach for this CBA, ARINC followed a disciplined systems engineering methodology that involved the use of five basic steps:

- Select the reference and alternative systems
- Identify key issues and concerns
- Develop the ground rules and assumptions for the analysis
- Define the cost element structure (CES)
- Select the appropriate model for the analysis

3.3.1.1 Reference System and Alternative Systems

The reference system(s) chosen for this CBA were aircraft structural components that provide either a load-bearing or critical flight control function (or both). These were the trailing edge structure and the vertical stabilizer. In addition, the engine mount was chosen as a reference system due to an expressed interest in that structure on the part of the air carrier community. The alternative system(s) to be considered for this CBA are the same structural components chosen for the reference system, but with an ASHMS capability incorporated.

Since each reference system is, as is typical, an existing operational system with an equivalent or similar mission relative to the alternative system, available historical data, from sources such as maintenance data collection systems and current operational databases, could be used to calculate the *relevant* LCC of the reference system. However, for each alternative system, historical data do not exist since ASHMS is yet to be implemented. Therefore, the expected nonrecurring and recurring cost were estimated for developing, acquiring and integrating the ASHMS capability, as well as the expected relevant life-cycle LSC for the system(s). Again, relevant cost, in this case, are those that are deemed likely to increase or decrease with the implementation of the ASHMS.

3.3.1.2 Key Issues and Considerations

The key issue in performing any CBA is whether sufficient reliability and maintainability (R&M), operational utilization, and LSC input data for the reference and alternative structural systems can be acquired for performing an accurate, realistic, and complete LCC analysis with reasonable confidence. Lack of sufficient LSC and R&M data would adversely influence the certainty and integrity of the CBA analysis and, thereby, the suitability and usefulness of the results.

To resolve this potential problem, we developed an analysis approach that facilitated the use of analogous aircraft system data, cost estimating relationships (CERs), and common economic, operations, and logistics factors, as necessary, to supplement or accommodate for data voids and shortfalls. This approach resulted in the derivation of an order-of-magnitude cost factor baseline that constituted a realistic and reasonable generic representation of the expected operational logistics support environment for most commercial and defense aerospace applications.

In addition to our concerns about obtaining R&M and LSC data for the reference system, we were also concerned about developing realistic projections for the nonrecurring and recurring investment costs associated with the development, acquisition, and support of viable ASHMS technology solutions.   To resolve this concern, we used engineering estimates for these costs to augment those cases in which adequate cost data could not be provided by the customer, vendors, or the users. In order to develop such engineering estimates, we obtained input both from the literature, and discussions with researchers, engineers, and other experts currently working in the field of sensor and health monitoring system development, on the factors that contribute to the cost element. Then, the median of these values was used to build up the baseline engineering estimate for that cost element. As would be expected for estimating the costs associated with emerging technologies, these values were expected to be realistic but to have a larger uncertainty than those for which "hard data" could be obtained. Therefore, we bounded the engineering estimates with upper and lower values that were representative of expected ranges in the AC of the sensors. Based on our analysis, we determined acceptable bounded ranges to be 50% below the AC baseline to 200% above the AC baseline. This range not only allows for uncertainty in the baseline estimate but also allows us to account for variability in the AC due to variation in the architecture of the ASHMS.

To alleviate the impact that use of input data from analogous systems data, CERS, and engineering estimates could have on the reliability of the CBA output, particularly for the alternative system(s), our analysis approach incorporates an approach in which we show the functional relationships between LSC and selected R&M cost factors (called cost drivers). Specifically, these cost drivers are varied over a bounded range of hypothetical values for the purpose of assessing the sensitivity of LSC as a function of each cost driver. In this way, the uncertainty of the results is mitigated, a more accurate portrayal of the expected LSC variability is provided, and a reasonable representation of the expected return on investment can be derived. Furthermore, as actual R&M and LSC data are acquired by the customer, the information from this CBA can be objectively used as a tool to forecast the cost effectiveness and benefit of future investment decisions.

Another issue was uncertainty with respect to the programmatic implementation of the long-term maintenance approach by the commercial airline user(s) with and without ASHMS capability. In other words, the precise logistics and maintenance plan must be in accordance with FAA directives but still varies from airline to airline. With respect to implementation of an ASHMS, certain airlines may elect to accommodate new maintenance practices differently than others. Further, one of the key opportunities for savings to be realized from an ASHMS is derived from the elimination, reduction, or streamlining of logistics support activities (associated with both scheduled maintenance and unscheduled maintenance) that are not necessary relative to structural integrity, maintenance condition, functional capability, or flightworthiness considerations. Therefore, in order for the air carriers to realize these savings, they must incorporate a maintenance program into their process that allows such reduction or streamlining.

We resolved this issue for the purpose of this CBA by assuming commonality between the airlines in terms of implementation, as well as no delay by individual airlines for steady-state implementation of enhanced ASHMS technologies. In addition, we mitigated variability by using composite data from several air carriers and other data sources. For example, since our research indicates that scheduled maintenance is being accomplished for most aircraft structures on an opportune basis coincident with scheduled maintenance requirements associated with other non-structural systems, we tailored our related cost parameters, CERs, and estimating methodologies accordingly.

3.3.1.3 Ground Rules and Assumptions

A fundamental prerequisite for performing an LCC analysis is a detailed definition of the ground rules and assumptions that will be used in conducting the analysis. The ground rules include a description of the relevant operations, maintenance, support, and logistics policies, considerations, and factors. The assumptions help bound the LCC estimates by defining the conceptual and technical scope of the analysis. Generally, the ground rules and assumptions should be clearly and succinctly described early in the analysis process. This permits their effective use in ensuring a consistent and reasonable focus for the analysis approach.

Whenever possible, the CBA ground rules and assumptions should be mutually reinforcing and consistent with the computational methodologies and algorithms for estimating the LCC of the reference and alternative systems.

The groundrules and assumptions that were used in performing this CBA fall under the following topics:

- Definitions (as previously described)
- Conceptual and technical approach
- Technology insertion

- Maintenance concept
- Reliability and maintainability (R&M)
- Cost formulation
- Model selection

A detailed listing and description of the groundrules and assumptions that were used in performing this CBA are provided in Section 4.

3.3.1.4 Cost Element Structure (CES)

The CES establishes a standard architecture and vocabulary for identifying, defining, and classifying the relevant cost associated with the LCC estimates for the reference and alternative systems. The CES selected for accomplishing an LCC estimate should always be carefully validated to ensure that all relevant cost has been appropriately identified and aggregated in a manner consistent with the approach, ground rules and assumptions, and model selected for performing the LCC estimate.

The CES that was developed for use in this CBA is shown in Appendix A to this document. Although the major cost categories and elements remained stable, the CES was tailored as the analysis matured (e.g., adding new or additional cost elements, or eliminating or changing current cost elements) in order to enhance the accuracy, realism, and completeness of the analysis relative to the CBA requirements as stipulated by the NASA LaRC.

The final CES shown in Appendix A is consistent with the technical approach selected for the CBA; logically aggregates the major relevant cost associated with the intended development, operational, and logistics support environments; and is compatible with the model selected for performing the LCC analyses. In summary, if a given cost element was considered to impact a change in the LCC associated with maintaining and supporting the aircraft, then that element and its cost were identified and included in the CES.

3.3.1.5 The LCC Model

LCC analyses usually are accomplished using an appropriate computer model to derive the reference and alternative baseline LCC estimates. Once these estimates have been validated, the model can then be used to perform the appropriate risk, sensitivity, and data comparison analyses needed for assessing the relative merits (benefits and consequences) associated with each.

The LCC model (LCCM) is basically a simplified economic representation of the real world. It provides the analytical structure from which the cost estimate is made. An LCCM typically develops cost projections for the three major phases of a system's service life: the RDT&E phase, the acquisition phase, and the operation and support phase. Within each of these phases, annual cost are calculated and aggregated for each cost category.

3.3.1.5.1 Types of LCC Models

Generally, most LCCMs fall into one of three types (each of which can be seen to use one or more of the LCC basic estimating methods described later in this section):

- Parametric models. A parametric model estimates cost using a set of complex mathematical or statistical equations that relate cost to system parameters such as design, performance, or operating characteristics, or the environment. These models are typically used during the very early stages of a program when cost-related historical data are limited or non-existent.

- Accounting models. An accounting model uses a set of relatively simple equations to calculate and aggregate cost elements using direct data inputs and cost factors. Accounting models attempt to represent what actually happens in the real world using a structured set of basic accounting relationships to quantify all the relevant variable factors associated with each cost element.

- Simulation models. These models typically use probabilistic computer simulations to assess the LCC impacts of a system's operational and performance characteristics, basing and deployment concepts, operations and maintenance plans, and provisioning and support requirements. Although very accurate, the large amount of data required to generate the simulation normally limits the use of such models to the later stages of a program, when sufficient amount of detailed data are available.

3.3.1.5.2 Selection of LCCM

In order to limit the scope and cost of this study, ARINC elected to base our analysis on the Cost Analysis Strategy Assessment (CASA) model[1], a commercially available engineering-based accounting model that allowed the flexibility to be tailored for this application. The equations used in CASA for quantifying the relevant cost elements are based upon generally accepted CERs that use detailed programmatic, technical, engineering, operations, and logistics data. Cost are computed and aggregated for each relevant cost element, and then these cost elements are consolidated into the major cost categories in "building-up" to a total program LCC projection. A more complete overview of the CASA model and its capabilities is found in Appendix B.

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[1] Originally developed for the U.S. Defense Systems Management College by Honeywell

Though the CASA model required tailoring for application to this study, we used it as a baseline over several other candidate models because of its flexibility, adaptability, precision, and ease-of-use in estimating the relevant cost elements associated with advanced technology aerospace systems. For example, the logical structure of CASA closely follows the LCC analysis processes and CESs commonly used by cost analysts. Furthermore, CASA conveniently incorporates various cost analysis and sensitivity assessment tools into one integrated model and it effectively met the following criteria that are usually considered in the selection of an appropriate LCCM:

- Consistency with CES. The model is consistent with the CES that applies to the analysis.

- Data Consistency. The data requirements of the model are consistent with the expected or actual quality and availability of data for the reference and alternative systems. Also, data used by the model should be derived from the most reliable and credible data sources.

- Flexibility. The model is flexible and adaptable enough to accommodate various analysis requirements and approaches, ground rules and assumptions, types and levels of data, and estimating methodologies and evaluation criteria.

- Simplicity. Since complexity in itself does not lend additional credibility to a model or its results, we preferred a model which was easily used.

- Usefulness. The model is applicable to standard management and decision-making activities and the modeling methodology is sensitive to changes in relevant design, procurement, and operational factors.

- Completeness. The LCCM adequately and correctly addresses all relevant cost elements that have been identified in the CES. Also, the LCCM is capable of reflecting the various policy considerations and decision parameters that impact the estimate.

- Validity. The computational methodologies of the LCCM are sound and realistic relative to the system's programmatic, operational, logistics, and environmental characteristics. Furthermore, the CASA LCCM has been shown to provide accurate results that are reproducible, auditable, and traceable.

Because of the uncertainty and risk relative to the maturity, fidelity, and integrity of the data to be used in this CBA, the unique CBA application environment, and the highly-specialized emergent technologies involved, ARINC did tailor the estimating algorithms and equations offered by the CASA model. Instead of focusing on projecting discrete point estimates for the reference and alternative systems, ARINC expressed CBA results in terms of the projected cost differences and benefits expressed as bounded ranges.

3.3.2 Customer And User Coordination

We believe that a successful cost analysis is facilitated by a continuous liaison between the cost analysis team, the customer, and any end users of the proposed technology. The purpose is to ensure that these "stakeholders" understand and accept the objectives, approach, and scope of the analysis. Therefore, specific topics, including the characteristics and specifications of the reference and alternative systems, the operations and support concepts, the ground rules and assumptions for performing the analysis, the relevant cost drivers, the cost to be included and excluded in the CES, the data sources, the estimating methodologies and cost models to be used, significant sensitivity and trade-off issues, and documentation, were each discussed at length with representatives from NASA LaRC and several of the commercial airlines.

In addition, ARINC provided NASA with regular status updates that apprised NASA of the progress and success of the CBA effort relative to the stipulated objectives, schedule milestones, and cost goals, as well as notifying them of the problems and issues encountered, mitigating and corrective actions taken, and preliminary results-to-date.

3.3.3 Life-Cycle Cost Estimation

3.3.3.1 Methodology

Though there are many methods for estimating the LCC of a reference system and its alternative, the techniques selected depend upon the maturity and stability of the program, and the accuracy, credibility, and completeness of the data that are available for input to the LCCM. In this case, as previously discussed, our cost estimating methodologies must be flexible enough to deal with emerging (yet to be implemented) technologies for which complete historical cost and R&M data do not exist, and with variability relative to intended operational implementation of ASHMS by the air carriers. Therefore, in an effort to most realistically estimate expected cost for the reference system and its alternative, ARINC has elected to use a mix of parametric, analogy, and engineering estimation techniques. (The CASA LCCM provides this ability.) These are briefly described as follows:

- Parametric estimation. Parametric estimation uses CERs to project cost. A CER is a mathematical or statistical equation that relates one or more characteristics of a system to one or more cost elements. Parametric estimating is especially useful in the early phases of a program when little historical data is available to support the estimate.

- Analogy estimation. Analogy estimation uses current and historical data about an existing similar system to estimate the cost of the proposed system alternative(s). For the estimate to be accurate, the existing analogous system should be similar in design and use to the proposed alternative system.

- Engineering estimation. This technique involves using a detailed “build-up” approach in which the system is decomposed into many lower level components, each of which is costed separately. The individual component costs are then consolidated into the engineering estimate.

3.3.3.2 Data Collection And Analysis

Three types of data are generally required for most LCCMs: programmatic data, technical data, and cost data. These data must be provided for both the reference system and proposed alternative system. Programmatic data are facts or assumptions about the system deployment and utilization, operational and logistics concepts, and support requirements. Technical data include the engineering specifications, operational characteristics, and performance capabilities of the system, with a primary focus on defining the R&M attributes of the system. Cost data are facts or assumptions about the dollar value of the resource requirements and consumption rates of the proposed and reference systems. Typically the focus is on manpower, equipment, and materials cost.

ARINC’s original intent was to use information provided by NASA, the air carriers, other Government agencies (e.g., the Departments of Transportation and Labor, the FAA, and the NTSB), and manufacturers as the primary source of data for the CASA model. Consequently, ARINC established direct communications with these agencies for the purpose of acquiring the data necessary for accomplishing the CBA. These communications were instrumental in providing the programmatic, technical, engineering, operations, and logistics data necessary for accomplishing the CBA.

However, in those instances where these data were not available or the data provided to ARINC were perceived as being incomplete, historical data from existing analogous aerospace systems were used, as appropriate. As appropriate, these data were:

- Obtained from consultation with reputable industry technical experts; researchers and scientists; operations and logistics managers, technicians, and support personnel; academicians; and financial consultants.

- Derived from appropriate engineering CERs.

- Obtained from available commercial or government data sources (e.g., Departments of Transportation and Labor publications, reports, and data summaries).

- Synthesized from analyses of existing analogous aerospace systems employed by the Department of Defense (DoD) and commercial air carriers.

As this information was acquired, ARINC verified and validated (V&V) this information and then entered it into the appropriate data models necessary for executing the LCCM.

In addition, ARINC conducted an extensive research effort to acquire the knowledge necessary for performing the CBA and validating the output results. At the same time, ARINC supplemented this information with data acquired from our other independent research efforts. For instance, ARINC has compiled a significant "knowledge base" of aircraft engineering, R&M, and cost data that we have obtained from our work with numerous industry, academic, and government research, acquisition, and logistics agencies. The results of this effort were used in the tailoring the CASA process and data models, accomplishing V&V of CASA data inputs, describing the relevant operational and logistics considerations, assessing and interpreting CASA outputs, and performing the desired sensitivity analyses.

In addition, ARINC has tentatively identified the top-level functional requirements that are relevant for achieving a viable ASHMS and is correlating these requirements with existing and projected capabilities for the purpose of bounding the expected development, acquisition, and support cost.

SECTION FOUR

GROUNDRULES AND ASSUMPTIONS

4.1 INTRODUCTION

A successful CBA requires a detailed and comprehensive description of the ground rules and assumptions that document the scope and limitations of the study. This section describes these ground rules and assumptions.

4.2 GROUND RULES AND ASSUMPTIONS FOR THE CBA APPROACH

The following ground rules and assumptions that are related to the conceptual approach, model selection, and data collection and validation were used by ARINC in performing this CBA.

4.2.1 Conceptual Approach

- The CBA focuses on the impact and benefits to large commercial air carriers of implementing and utilizing ASHMS for selected airframe components. The impact to General Aviation is considered to be outside the scope of this study.

- The CBA focuses on estimating only *relevant* LCC and LSC differences between the reference system(s) and the respective alternative system(s). As previously defined, relevant cost are those economic factors that impact the decision-making process for possible implementation of ASHMS. LCC, AC, and LSC will be computed in terms of composite dollar values (in which data from several sources is combined and integrated). This facilitates using a more flexible baseline for estimating the LCC, AC, LSC, and ROI.

- The CBA does not present cost results as discrete point estimates for the LCC, AC, LSC, or ROI associated with the reference and alternative system(s). Rather, a domain or range of expected LCC, AC, LSC, and ROI was computed for both the reference and alternative systems. Using a domain of expected cost allows the upper and lower limits for this cost to be estimated as thresholds bounding the expected results. It also facilitates comparing the reference and alternative systems in terms of how cost vary as a function of the relevant cost drivers.

- LCC, AC, LSC, and ROI expected cost domains are estimated at the aircraft fleet level for each aircraft class (composite make/model), rather than at the individual aircraft or component level, for the reference and alternative systems. Separate estimates were not developed for individual aircraft or structural components due to the limited availability, reliability, integrity, and completeness of R&M, operational utilization, and logistics support data.

4.2.2 Model Selection

Selection of the LCCM to be used for this CBA was based on the following criteria:

- Compatibility with proven CBA methods
- Consistency with:
  - Cost element structure (CES)
  - Process and data models
  - Cost estimating relationships (CERs)
  - Sensitivity analysis methods
  - Flexibility, adaptability, and ease-of-use

Other critical selection and tailoring issues that were considered in the selection of the LCCM included:

- Emerging technologies to be used for the ASHMS
- Data availability, reliability, and completeness
- Programmatic uncertainty and risk

4.2.3 Data Collection and Validation

- This CBA focuses on three pre-selected principal structural elements. These are the vertical stabilizer, the trailing edge structure, and the engine mount.
- All of the required cost and R&M data either exist and can be obtained, or can be derived or estimated on the basis of appropriate CERs, consultation with reputable experts in the field of interest, or data from analogous sources.
- Cost and R&M data for analogous systems can be used for the purpose of data validation.

- Cost and R&M data from aging systems will be treated separately from that of newer aircraft.

Note that the construct of these ground rules and assumptions intentionally allows some flexibility in the approach for performing the CBA, so that ARINC could develop generic cost factors and data baselines for estimating those cost elements for which NASA or the end users could not provide data. Although this approach may result in the use of data that differ in magnitude from cost actuals, it does not significantly diminish the relevance or usefulness of the cost analysis for its intended purpose. Using this modified approach, a viable and credible CBA was accomplished that provides NASA with critical comparative information regarding the potential order-of-magnitude economic impacts of acquiring and implementing viable ASHMS solutions for aircraft systems.

4.3 GROUND RULES AND ASSUMPTIONS RELATED TO ASHMHS

The following ASHMS ground rules and assumptions were made in performing this CBA:

- Emerging technology opportunities and operational trends favor replacing conventional off-line NDE/NDI techniques (e.g., eddy current, ultrasonic, and x-ray) and localized "indirect" sensing capabilities (that require using complex correlation routines based on a priori knowledge of behavior) with sophisticated, yet affordable sensing technologies that are capable of:
  - Direct macroscopic sensing
  - Distributed multifunctional sensing. Multifunctional sensing refers to sensing in which more than one attribute can be measured by a single sensor, or multiple functions (e.g., sensing and actuation) can be performed with a single sensor.
- Existing aircraft structures will be retrofit for integration of an ASHMS capability.
- The ASHMS will be optimally configured to accurately detect, characterize, and track the integrity and condition of the selected aircraft structures.
- Structures with embedded ASHMS components are treated as integrated components.
- An "all or none" implementation perspective is used for the integration of the technology alternatives. In other words, either all aircraft in the fleet will possess the ASHMS capability, or no aircraft will possess the capability.

- Accurate in-situ sensing of critical condition attributes and material properties is performed using ASHMS. The critical condition attributes may include
  - Physical
  - Chemical
  - Thermomechanical
  - Morphological

- The optimal technological configuration is an integrated, distributed network of multifunctional sensors, signal processing, and data analysis components, with sensor distribution predicated on the area of coverage and complexity of the component. For the purposes of this analysis, the baseline ASHMS includes 100 sensor elements for the trailing edge structure; 150 sensor elements for the engine mount; and 200 sensor elements for the vertical stabilizer. It is further assumed that sensor selection is primarily driven by performance-based operational requirements.

- Any loss of functionality of individual sensors (such as due to malfunction or damage) within ASHMS will not impact the statistical reliability of ASHMS to report the condition or integrity of the component.

- Sensor technologies that are viable as candidates for an ASHMS technology include:

  - Ultrasonics

    - Acoustic emission – damage and degradation

    - Fiber ultrasonics – fiber/matrix interface, mechanical, and mircrostructural properties

    - Piezoelectric (PZT) – mechanical properties

  - Fiber optic sensors – physiochemical properties (e.g., strain, temperature, corrosion, and cracking)

  - Microelectromechanical systems (MEMS) – micro-thermomechanical properties

  - Remotely queried (e.g., wireless) sensors

- Data collection occurs inflight but detailed data analysis for life-cycle maintenance management may initially be ground based. Data download for analysis occurs at one Depot location.

- The ASHMS is implementation ready, operationally reliable, flight worthy, survivable in the operational environment, and user friendly.

4.4 GROUND RULES AND ASSUMPTIONS FOR THE MAINTENANCE CONCEPT

The following maintenance concept assumptions were made in performing this CBA:

- Earlier detection and repair of damage, defects, and degradation may result in maintenance streamlining and cost saving opportunities.

- Maintenance (unscheduled and scheduled) will be performed at major depot facilities (one per user).

- Most corrective maintenance can be performed on an "on-condition" basis using ASHMS.

- ASHMS component maintenance will be performed opportunistically during maintenance of the host structure(s)

4.4.1 Unscheduled Maintenance

- Unscheduled corrective maintenance is currently performed when damage, defects, or degradation are discovered and reported as the result of :

  - Pre- and post-flight inspections by aircrew and support personnel

  - Service checks (e.g., each day, not later than (NLT) every 7 days)

  - "A-checks" (e.g., NLT every 250 hours)

  - "B-checks (e.g., NLT every 6 months or 480 hours, whichever occurs first)

- Calibration, repairs, and overhauls are accomplished in accordance with structure repair manuals (OEM) and service bulletins (FAA)

4.4.2 Scheduled Maintenance

- Scheduled maintenance is accomplished in accordance with specified check and inspection schedules, including:

- Operational checks - inspections or examinations to determine general condition and to assess functionality and suitability for intended purpose (no quantitative standards)

- Inspections - comprehensive examinations of condition and functionality against prescribed standards and specifications

- Bench checks - functional or visual checks in-shop against prescribed standards and specifications to assess serviceability and determine the need for adjustment, calibration, repair, or overhaul

• Maintenance intervals are derived to comply with FAA Certification Maintenance Requirements (CMRs)

  - Types certificates are only valid when CMRs are performed at the specified time (FAA Advisory Circulars AC25.1309-1A, 120-17A, 121-1A)

  - Means of ensuring the detection of latent defects that would remain undetected until subsequent failure resulted in a hazardous event

• Scheduled maintenance inspection intervals are specified for:

  - Accident damage (AD)

  - Environmental deterioration (ED)

  - Fatigue damage (FD)

  - Airworthiness limitation instructions (ALIs)

• Scheduled maintenance intervals are documented in:

  - Structural and zonal inspection specifications

  - Airworthiness limitation instructions and directives

  - Engineering and routine maintenance specifications

• The focus of scheduled maintenance is on performing detailed inspections and checks of:

  - Structurally significant items (SSIs) - structures that significantly affect safety and reliability or have a direct operational or economic impact

- Principal Structural Elements (PSEs) - structures whose failure, if undetected, could lead to loss of aircraft. Candidate PSEs include:

  - Wing boxes and tees
  - Skin panels
  - Pressure bulkheads
  - Skin splices
  - Spars
  - Engine mounts
  - Wing structures, stabilizers, and control surfaces

- Safe-life structures - structures that withstand repeated variable loads without detectable cracks or degradation (e.g., landing gear components)

- The protocols for scheduled maintenance inspections and checks are:

  - Time-phased to ensure 100% fleet coverage over specified schedule w/o impacting operations

  - Not-later-than (NLT) a specified number of flight hours, days, or months for both initial and repeat inspections and checks. For example, representative intervals for many SSIs and PSEs are:

    - Flight Hours:

Service:	Daily / 7 days
A-Check:	150-400 hours
B-Check:	400-1000 hours
C-Check:	3000-5000 hours

    - Calendar Days/Months:

Service:	Daily / 7 days
A-Check:	30-90 days
B-Check:	90-180 days
C-Check:	24-30 months

  - Based upon 100% sampling or statistical sampling methods.

- Scheduled maintenance requirements and frequency can be reduced using ASHMS (e.g., “C-check” intervals may be increased)

4.5 GROUND RULES AND ASSUMPTIONS RELATED TO R&M

- Aircraft structures do not usually fail catastrophically.
- Aircraft structure designs are fail-safe under standard conditions.
- Aircraft structures are susceptible to damage and degradation that can be extensive, yet hidden, and therefore difficult to detect or characterize. This damage and degradation can be the result of:
  - Corrosion, fatigue cracking, or combined failure modes
  - Damage suffered during ground-based maintenance, operations, handling, and movement.
  - Impact with ground vehicles, equipment, or other aircraft
  - Bird strikes
  - Lightning strikes
  - Exceeding operational limits or service safety envelopes
- Uncorrected damage, defects, flaws, and deterioration can adversely change structural performance, functionality, condition, and integrity.
- Use of an ASHMS will allow structural health and condition (e.g., damage, defects, and degradation) to be:
  - Detected dynamically in-flight
  - Detected without teardown or use of ground-based NDE/NDI
  - Corrected before airworthiness is compromised (e.g., barely visible damage [BVD])
- The embedment of an ASHMS will not significantly degrade the performance, behavior, or inherent reliability of the component.
- Use of an ASHMS will improve resource availability and reduce maintenance downtime.

- Non-critical sensor failures or malfunctions will not be repaired.

- R&M inputs will be based on a mature system, steady state, and non-degraded condition frame of reference.

- Detailed R&M data analysis and management will be ground-based.

4.6 GROUNDRULES AND ASSUMPTIONS FOR COST FORMULATION

- The CASA LCCM was used to generate the expected cost domains for each relevant cost element. LCCM equations and algorithms are described in Appendix C.

- Sensitivity algorithms were used to assess the sensitivity of the cost drivers to relevant cost factors.

- LCC results are not expressed as discrete dollar-value point-estimates.

- LCC results are expressed as estimated ranges in base year differential dollars (LCC savings), not absolute dollars.

- The data inputs for the LCCM were derived as composite projections that are globally representative of real-world actuals.

- A total fleet frame of reference by aircraft class was used.

- RDT&E cost of ASHMS is passed through to the air carrier in the AC of ASHMS. Therefore, RDT&E cost of ASHMS is not explicitly estimated for the purpose of this study.

- Sunk cost (cost that are not recoverable or have little or no foreseeable impact on the use of the ASHMS technologies) are not addressed.

- Impact of the ASHMS implementation and utilization on operating revenue is considered outside to be the scope of this CBA.

- The LCCM process and data models were tailored to accommodate specialized operational applications and logistics support concepts; data availability, reliability, and completeness; and “real-world” conditions.

- The consideration of the influences of carrier-unique aircraft utilization and logistics support policies, operations and destination (O&D) profiles, and operating cost (e.g., liability, legal, fuel consumption and insurance cost) on LCC are considered to be outside the current scope of this CBA.

SECTION FIVE

COST ANALYSIS

5.1 COST DRIVERS

Based on our preliminary research, the CASA model indicated that the following R&M and cost factors were most likely to influence the cost differentials between the reference structural systems and their alternative ASHMS systems:

- Mean time between maintenance (MTBM) for both scheduled and unscheduled maintenance
- Mean time to repair (MTTR) for unscheduled maintenance
- Mean time for scheduled maintenance (MTSM)
- Retest OK (RTOK) rate (Inability to find a reported fault during subsequent bench test)
- Support equipment utilization factor
- Support equipment total unit cost
- Material cost per repair

Consequently, ARINC analyzed the impacts of changes in each of these factors on changes in R&M and LCC that might result from implementation of an ASHMS technology. This was accomplished by independently varying each of the relevant cost drivers, over a specified range of variability (0 to 50 percent improvement), to assess the sensitivity of life-cycle LSC to these drivers. The expected LSC savings domains were then computed by subtracting the respective alternative system LSC for each specified sensitivity value from the corresponding LSC for the reference system. The results of this sensitivity analysis served as the primary computational frame of reference for projecting the LCC domains and differentials between the reference and alternative systems.

The fundamental objective of the sensitivity analysis was to provide insight into the impact that individual cost or R&M factors have on the LCC savings and ROI that might be realized with implementation of ASHMS for the structural components under investigation. However, it should be noted that since ASHMS has not yet been functionally integrated into operation, any quantification of the impact on the R&M

factors would be a theoretical projection. While other studies have attempted to predict the impact an ASHMS might have on maintenance requirements [1], we felt that the most comprehensive analysis for NASA would be provided by showing the variability over the previously specified probable worst-case to best-case range (i.e., 0 to 50 percent improvement in those cost factors). In this way, as NASA considers various independent technology candidates for ASHMS, and the impact on the maintenance requirements is better defined, the results of this analysis can be used as a basis for projection of LCC savings.

Note: Most cost models use component mean time between failures (MTBF) data for computing the LCC for unscheduled maintenance. However, our research indicates that most maintenance performed on aircraft structures is not the result of component failures caused by latent design deficiencies, engineering defects, or fabrication, materials, and workmanship imperfections. Rather, maintenance on these structures is primarily performed due to such factors as:

- Operationally induced degradation such as corrosion, fatigue cracking, and combinatorial modes
- Damage caused by ground handling accidents (e.g., surface puncture and gouging, damage due to impact with equipment, tools, vehicles, or personnel; surface indentation, and leading edge and corner damage due to impact)
- Fastener over-torque or wear
- Foreign object damage
- Bird and lightning strikes
- Other accidents caused by the man-machine-environment interface

Consequently, ARINC decided to use MTBM (expressed computationally as mean flight hours between maintenance actions), instead of MTBF, as the primary indicator of the expected unscheduled and scheduled maintenance intervals for structural components. This allows a more realistic and accurate modeling of the LCC impacts associated with implementing ASHMS, since this technology can provide a viable means of detecting and diagnosing the types of aircraft structure damage that would most likely result in the generation of a maintenance action.

5.2 LCC ESTIMATING

A separate LCC estimate and data analysis was performed for each structural component by aircraft class as follows:

- Trailing edge for aged aircraft (i.e., in service greater than 20 years)
  - ⇒ 3-engine aged aircraft, e.g., DC-10, B-727
  - ⇒ 4-engine aged aircraft, e.g., B-707, B-747
  - ⇒ 2-engine aged aircraft, e.g., DC-9

- Trailing edge for current generation aircraft (i.e., in service less than 20 years)
  - ⇒ 3-engine aircraft, e.g., MD-11
  - ⇒ 2-engine aircraft, e.g., A-300 and A-310.

- Vertical stabilizer spar for aged aircraft
  - ⇒ 3-engine aged aircraft, e.g., DC-10, B-727
  - ⇒ 4-engine aged aircraft, e.g., B-707, B-747
  - ⇒ 2-engine aged aircraft, e.g., DC-9

- Vertical stabilizer spar for current generation aircraft
  - ⇒ 3-engine aircraft, e.g., MD-11
  - ⇒ 2-engine aircraft, e.g., A-300 and A-310.

- Engine mount for aged aircraft
  - ⇒ 3-engine aged aircraft, e.g., DC-10, B-727
  - ⇒ 4-engine aged aircraft, e.g., B-707, B-747
  - ⇒ 2-engine aged aircraft, e.g., DC-9

- Engine mount for current generation aircraft
  - ⇒ 3-engine aircraft, e.g., MD-11
  - ⇒ 2-engine aircraft, e.g., A-300 and A-310.

In addition, for the purpose of this CBA, we studied several aged DoD aircraft, including the KC-10, KC-135, C-9, and C-5, because these systems have structurally analogous commercial counterparts, but are much older. Since we suspect that the age of the aircraft will significantly influence the amount of structural maintenance required, and therefore the utility and benefit of an on-condition or condition-based maintenance approach using ASHMS, we used the results of this analysis to project maintenance requirements for the commercial airframe counterparts as these systems continue to age.

For each structural system selected for study, ARINC used the cost and R&M factor data provided in Appendix D as inputs to the tailored CASA LCCM to establish the initial life-cycle LSC baselines for the reference systems. As discussed in the previous section, these input data were derived to be representative of real world conditions from research, operations and maintenance (O&M), engineering, and marketing data obtained from commercial air carriers, industrial, government, and academic sources. (For reasons of protection of confidentiality and company- proprietary or -sensitive data, actual O&M data obtained from commercial sources are not provided in this document and were not directly used as inputs. Rather, composite data integrated from multiple sources were used, as previously discussed.)

The LSC baseline estimates derived from the input of these data into the LCCM served as the primary frame of reference for performing the LCC sensitivity analysis for estimating the expected LSC cost domains for the reference and alternative systems. Specifically, the computed LSC baseline results constituted the life-cycle LSC reference baseline for the current technology base (i.e., without ASHMS) for each structural component under study in the CBA. In order to provide insight into the relevance of each cost element in the CES, the LSC results are broken out, in graphical format, to show the projected life-cycle LSC for each cost element. These results for the reference system LSC baselines for the candidate systems studied in this CBA are presented and discussed in Section 6.0.

ARINC then applied the sensitivity factors provided in Appendix E to the relevant R&M and cost factors used as inputs for computing the LSC baselines for the alternative systems as a function of the expected change in R&M resultant from the implementation of an ASHMS. The results were then used to construct the expected LSC cost domains of the alternative systems as a function of variability in these cost drivers. This approach facilitates a disciplined and structured consideration of the question, “What happens to LSC if the selected input cost factor is changed in accordance with the specified sensitivity factors and all other cost factors remain constant?” The results of this analysis were then synthesized into tables and graphs that depict the sensitivities of LSC to the key R&M and cost factors.

For each candidate structural system, ARINC then used the projected investment cost for implementing and utilizing ASHMS on existing airframe structures, provided in Appendix F, as inputs to the LCCM to establish the AC baseline for the alternative systems. Again, as discussed in the previous section, these input data were derived to be representative of real world conditions using research data obtained from air carrier, commercial, government, and academic sources. The results are presented in the following section.

5.3 Return on Investment and Break-Even Point Estimating

ARINC estimated LSC separately for the reference and alternative systems in this CBA to facilitate the computation of ROI and to provide NASA insight into the impact that implementation of an ASHMS would have on the overall cost associated with maintenance and support of an aircraft fleet equipped with an ASHMS capability. ARINC computed the ROI by calculating the LSC savings (in base year dollars) associated with each ASHMS alternative less the expected investment cost (i.e., AC including RDT&E, integration, and initial support cost). ARINC then used this information to compute the annual rate of return on investment for each specified alternative for each candidate system over a 20-year life-cycle of the aircraft. In order to provide a metric by which the alternatives could be compared, we then computed the annual percentage rate (APR) of ROI to provide insight into the average percentage of the initial investment that would be recouped annually. This APR was determined by divided the annual ROI by the AC of the ASHMS. In each case, this series of computations were made for the AC predicated on the baseline ASHMS architecture (i.e., having the number of sensors as previously defined, for each structure), then for the upper AC bound (baseline +200%) and the lower AC bound (baseline – 50%) to project the impact to ROI as a function of the variations in the AC of ASHMS alternatives.

At the request of NASA LaRC and the suggestion of the air carriers, and in order to provide a purer basis for comparison of the economic feasibility of implementing and utilizing ASHMS over the expected life cycle, ARINC computed the break-even point (BEP). The BEP was determined by dividing the expected investment cost by the rate of ROI. This provides the period of time required to recoup the initial investment in ASHMS.

SECTION SIX

CBA RESULTS AND DISCUSSION

6.1 INTRODUCTION

The following section documents the results of the quantification of projected cost benefit associated with the development, integration, and implementation of a viable ASHMS into the candidate structure systems for commercial air carriers.

6.2 EXPECTED LSC SAVINGS

As previously discussed, ARINC used our tailored CASA sensitivity algorithms to generate the expected life-cycle LSC cost domains for the reference and alternative systems for each candidate system studied. The results of this analysis were then synthesized into the cost savings graphs shown in Figures 1-1 through 1-15 that depict the sensitivity of life-cycle LSC to the key R&M and cost factors identified in Section 5.0. (Figures 1-1 through 1-15 are provided at the end of Section 6). These graphs can be interpreted to show the effect that changes in a particular cost driver (from 0 to 50%) will have on the overall life-cycle LSC savings for each cost element. Therefore, these graphs show quantitatively which cost drivers will most influence the potential savings associated with implementation of an ASHMS.

For example, our analysis of these results indicated that cost due to maintenance frequency drivers (i.e., number of scheduled and unscheduled maintenance actions) were the dominant cost drivers in impacting LSC differential between the reference and alternative systems of the candidate structures. Therefore, the expected life-cycle LSC domains expressed as a function of the variance in scheduled and unscheduled maintenance actions were plotted as graphs. These graphical data provide focused insight into the strong correlation that exists between maintenance requirements (expressed in terms of generated maintenance actions) and LSC. These graphs are shown in Figures 2-1 through 2-15. (Figures 1-1 through 1-15 are provided at the end of Section 6.)

6.3 EXPECTED RETURN ON INVESTMENT

The expected ROI for the ASHMS alternative systems were computed as a function of the expected changes in LSC savings, if any, less the expected acquisition cost (i.e., the investment cost associated with developing, procuring, and integrating the ASHMS). The results of these computations are portrayed in the ROI graphs provided in Figures 3-1 through 3-15 and 4-1 through 4-15. These charts can be used to forecast the cost-effectivity and benefit by providing a measure of the amount of time it will take to recover the initial investment associated with ASHMS implementation and utilization.

This measure is described by the annual percentage rate (APR) of return on investment and BEP, for each ASHMS alternative.

Although the APR of ROI and BEP are functionally dependent upon the improvement that the implementation of ASHMS has on the maintenance requirement, it is also important to note that for a given R&M improvement, the APR of ROI and BEP are significantly different for aged versus current generation (i.e., newer) aircraft systems. Table 1 provides a direct comparison of these factors for the structural components of three-engine aircraft considered in this study for a given R&M improvement (i.e., reduction in maintenance requirements) of 35%. (Note that for this comparison, we have selected 35% improvement in maintenance because our research and experience indicate that this is a reasonable and realistic expectation for the improvement that ASHMS would provide.)

Table 1: Comparison of ROI and BEP for 35% Reduction in Maintenance Requirements

Structure	Aircraft Class	Break-Even Point (years)	Annual Percentage Return on Investment (%/yr)
Trailing Edge Structure	2-engine turbojet	2.5	40.0
(100 sensors/structure)	2-engine turbojet (aging)	2.3	43.5
	3-engine turbojet	2.8	35.7
	3-engine turbojet (aging)	2.4	41.7
	4-engine turbojet (aging)	2.3	43.5
Vertical Stabilizer	2-engine turbojet	6.2	16.1
(200 sensors/structure)	2-engine turbojet (aging)	5.9	16.9
	3-engine turbojet	7.0	14.3
	3-engine turbojet (aging)	6.0	16.7
	4-engine turbojet (aging)	6.0	16.7
Engine Mount	2-engine turbojet	2.7	37.0
(150 sensors/structure)	2-engine turbojet (aging)	2.5	40.0
	3-engine turbojet	2.8	35.7
	3-engine turbojet (aging)	2.5	40.0
	4-engine turbojet (aging)	1.9	52.6

6.4 DISCUSSION OF RESULTS

In general, the results corroborate an intuitive notion: that the more maintenance that is required for a given structural component, the greater the likely LCC savings that would be incurred by the implementation and utilization of the ASHMS. Specifically, we found that:

- If the expected maintenance requirements for structural components (in terms of maintenance actions, turnaround time, and support cost) can be reduced as the result of implementing an ASHMS capability, the expected life-cycle LSC savings for the ASHMS alternative relative to the reference system will increase - with the alternative system becoming increasingly more cost-effective as maintenance requirements decrease from the reference.

- As the expected maintenance requirements for structural components (in terms of maintenance actions, turnaround time, and cost) are reduced as the result of implementing an ASHMS capability, the expected ROI for implementing the ASHMS alternative will increase - with the alternative system becoming increasingly more cost-effective as maintenance requirements decrease from the reference.

- For both the engine mount and trailing edge structure, an improvement (reduction) in maintenance requirements of 30% or greater results in a BEP of less than 3 years for both aged and current generation aircraft systems. The vertical stabilizer, which is a larger structure requiring a significantly larger number of sensors, requires a substantially longer period of time to recover the AC of the ASHMS. As a general rule, this would also be true for more complex structures and large structures, both of which would presumably requires more sensors for adequate coverage.

- In general, for aged aircraft, where the maintenance requirements for structural components are high, there is a greater opportunity for realizing increased LSC savings, higher APR of ROI, and improved BEPs if ASHMS implementation results in significant and immediate reductions in maintenance requirements can be facilitated. Furthermore, for aged aircraft, even if only modest reductions in maintenance requirements can be achieved (e.g., 20 to 30 percent reductions in maintenance requirements), significant LSC savings can still be realized.

- If scheduled maintenance intervals (i.e., MTBM) for structural components can be substantially increased with implementation of ASHMS, the expected life-cycle LSC savings and ROI will increase significantly. Our analysis indicates that, in most cases, a realistic 30 to 40 percent improvement will result in cost savings and BEP (i.e., recovery of investment) in less than three years for the engine mount and trailing edge structure.

- If the average infrastructure cost and turnaround time (e.g., MTSM) for performing scheduled maintenance (e.g., labor and material cost, component teardown, support equipment maintenance, NDE/NDI utilization, and rework) can be substantially reduced with implementation of ASHMS, the expected life-cycle savings and ROI will increase significantly. Again, in most cases, a 30 to 40 percent improvement will result in cost savings such that the BEP will be less than two years, on average.

- As the number of components on which ASHMS is used increases (for a given aircraft), the rate of ROI increases with a corresponding decrease in BEP. This can be observed by the less than 2 year BEP for the engine mount on the 4-engine aircraft relative to the 3- and 2-engine variants. This can be principally attributed to the economies of scale and compounding effects.

Throughout this discussion, we have focused on a 30-40% improvement in maintenance (reduction in maintenance requirements) as a baseline for discussion of LCC savings, ROI, and BEP. As previously stated, we believe that this projection is operationally realistic for most state-of-the-art and emerging sensor systems, based upon our experience as well as the experiences of individuals in the field. However, it should be noted that respected professionals in the "Smart Structures" community have projected a slightly more optimistic impact on reduction in maintenance requirements. Specifically, researchers at Stanford University have reported that the implementation of an ASHMS type technology may result in maintenance improvements of up to 45%. In this case, which we might call a best-case scenario based on the information we have to date, the expected BEP would be within less than two years.

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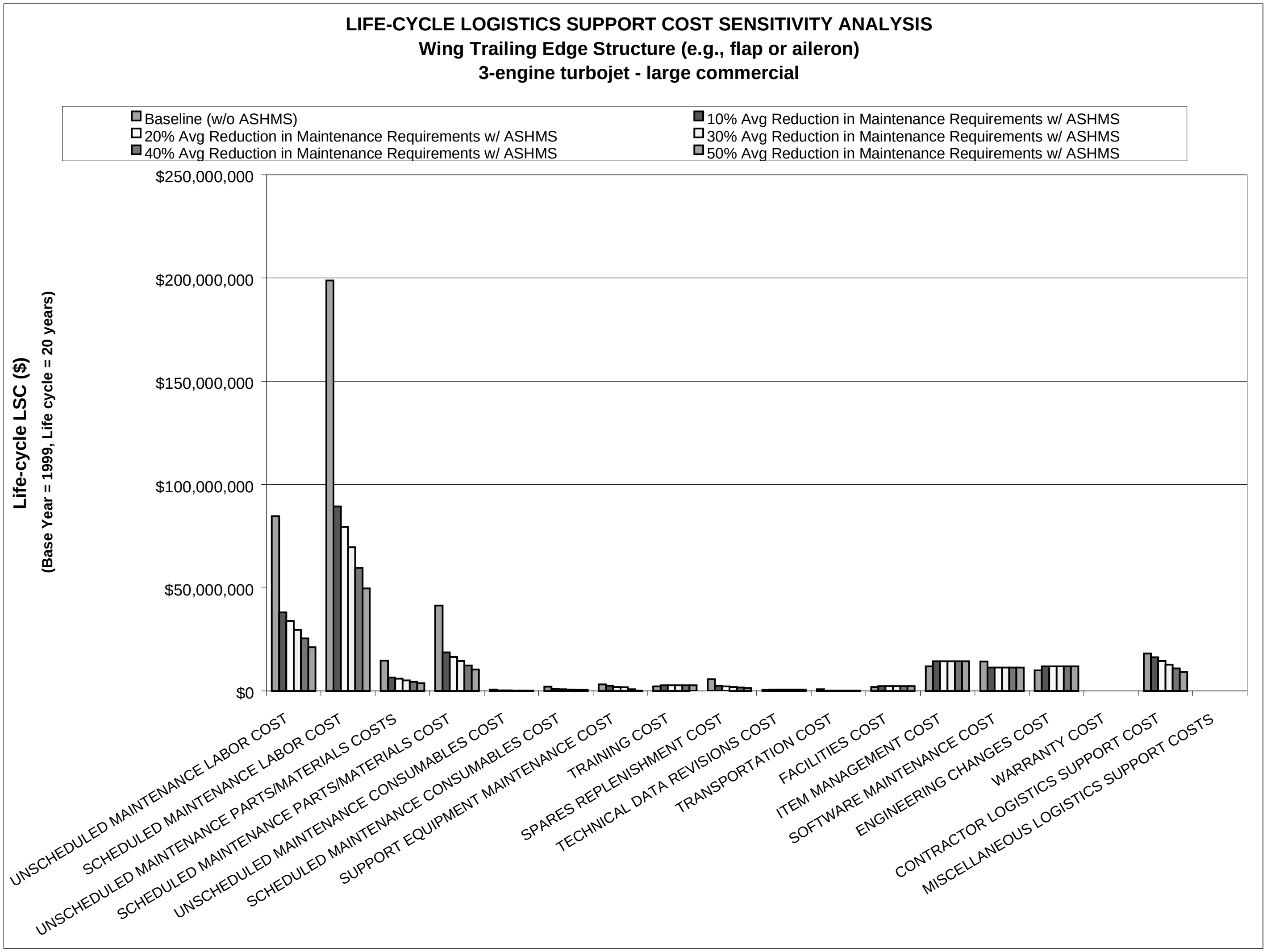


Figure 1-1: LSC Sensitivity Analysis, Wing Trailing Edge Structure, 3-Engine Turbojet

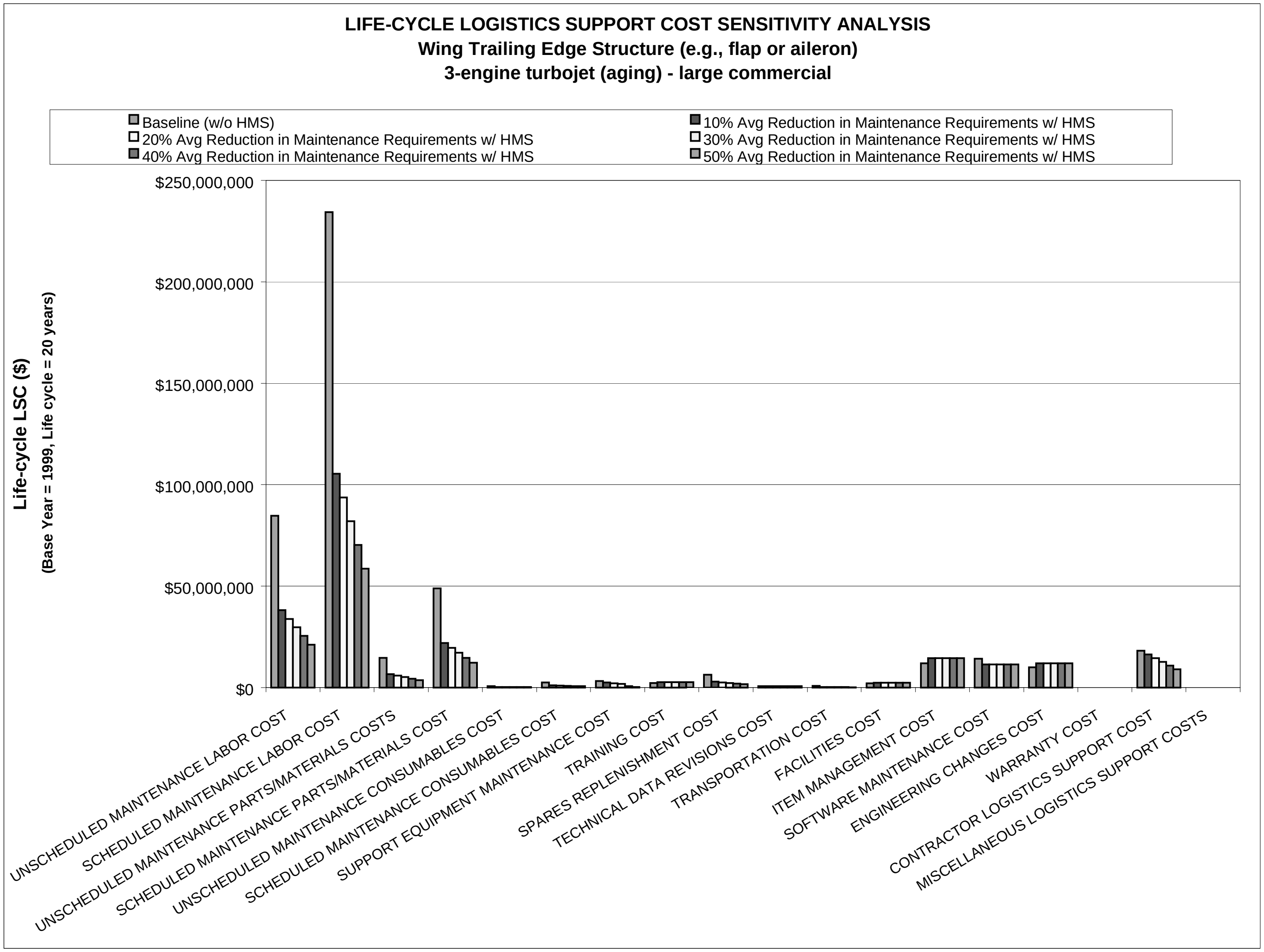


Figure1- 2: LSC Sensitivity Analysis, Wing Trailing Edge Structure, 3-Engine Turbojet (aging(

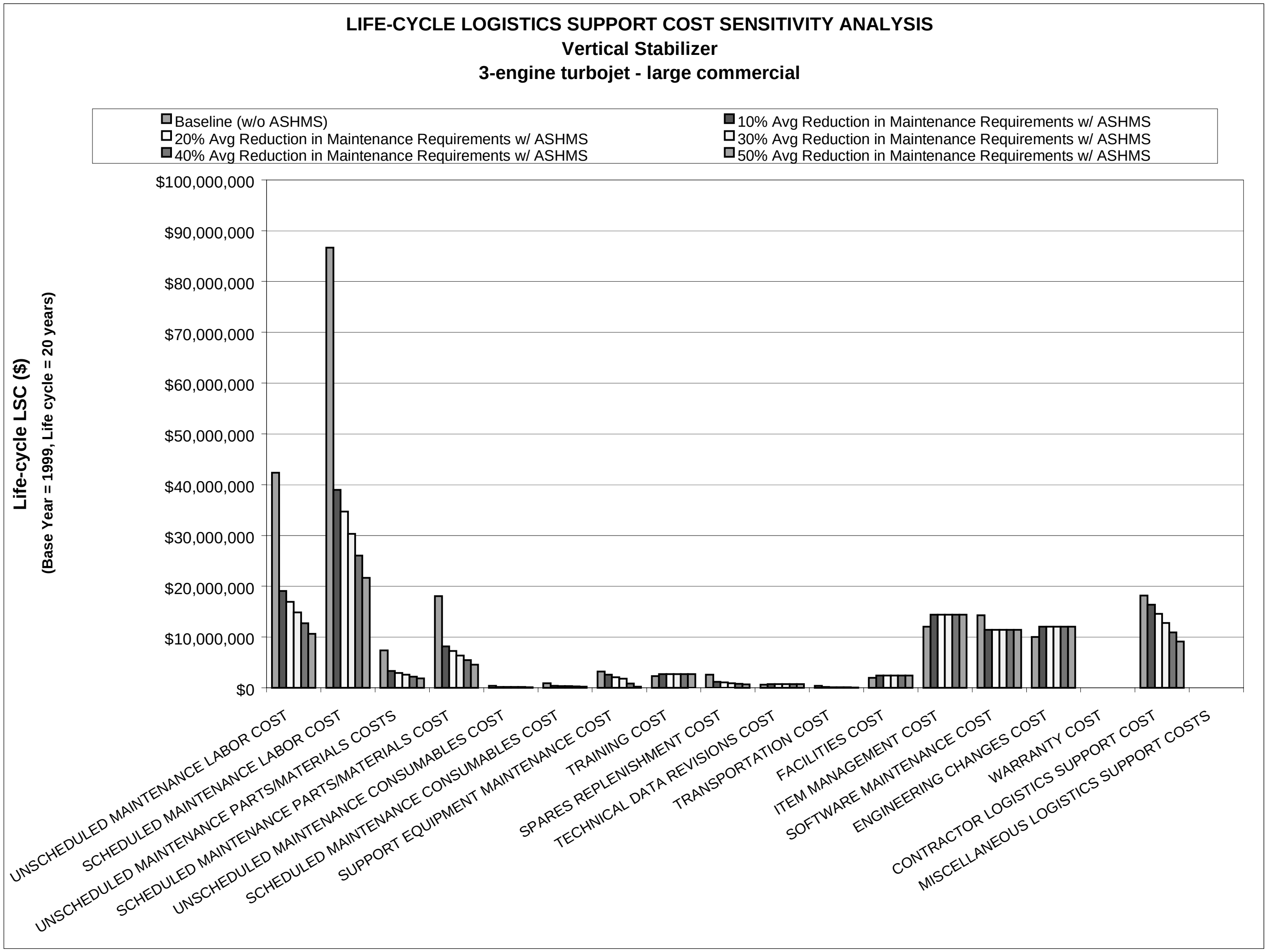


Figure 1-3: LSC Sensitivity Analysis, Vertical Stabilizer Edge Structure, 3-Engine Turbojet

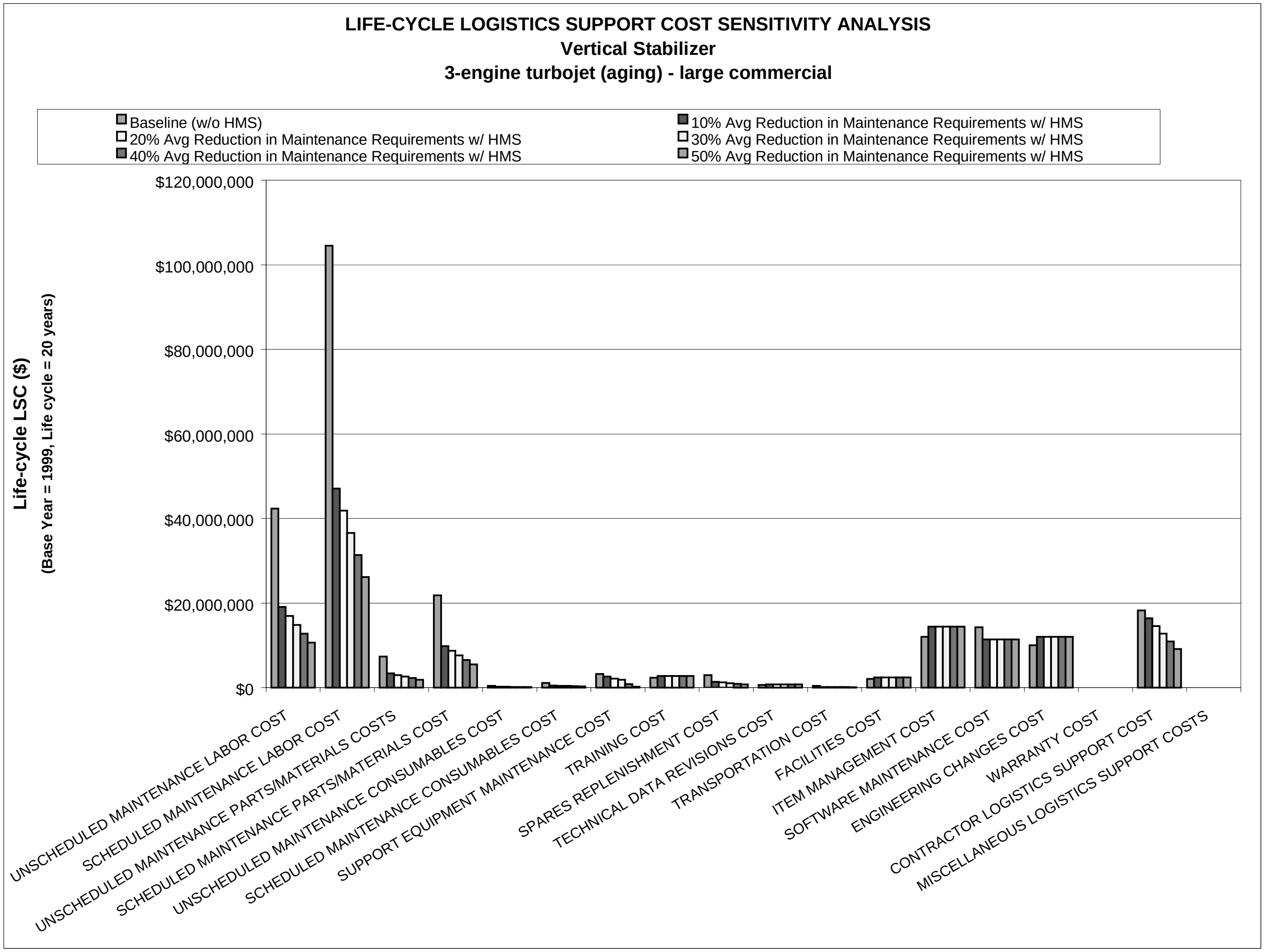


Figure 1-4: LSC Sensitivity Analysis, Vertical Stabilizer, 3-Engine Turbojet (aging)

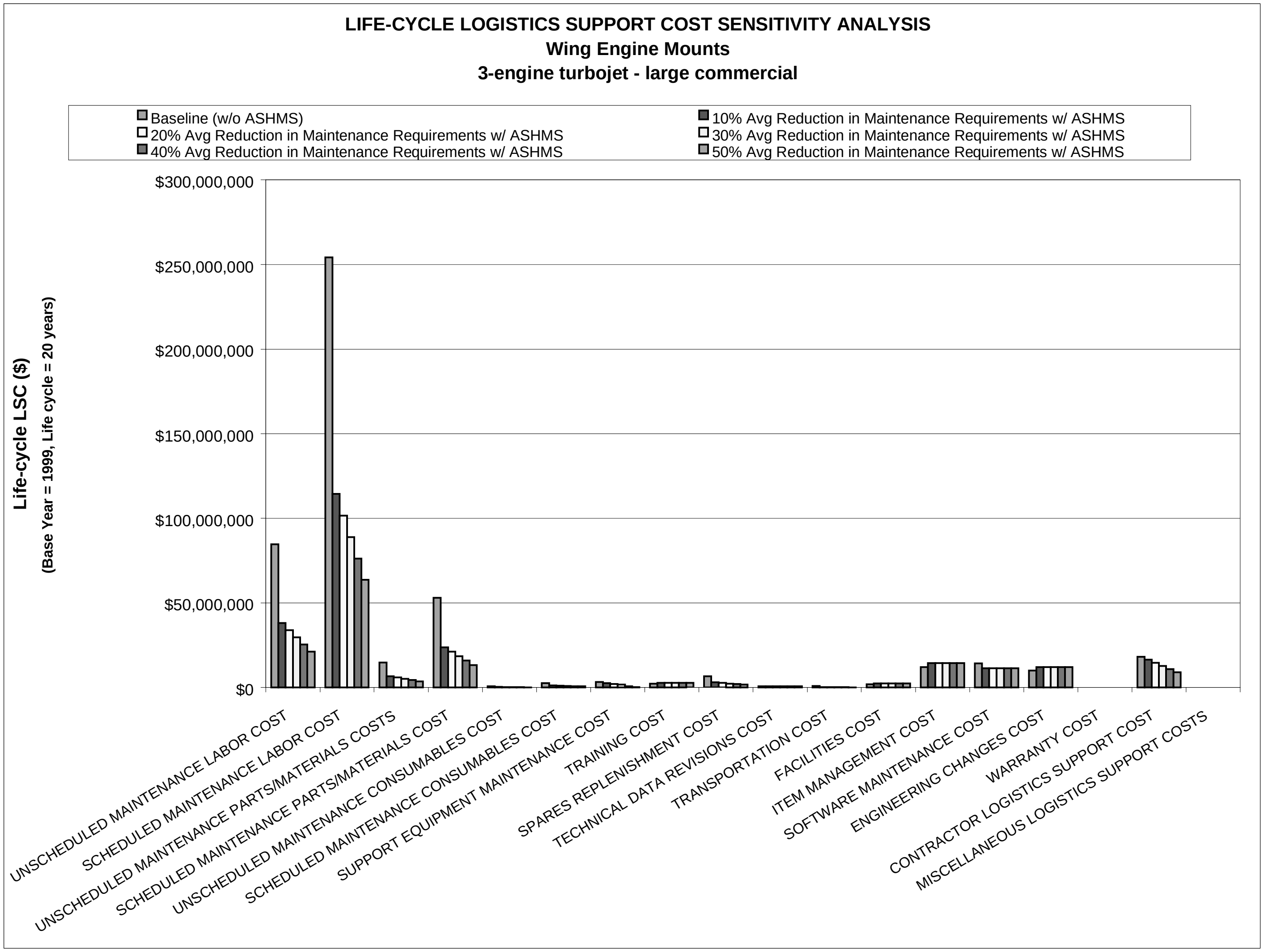


Figure 1-5: LSC Sensitivity Analysis, Wing Engine Mounts, 3-Engine Turbojet

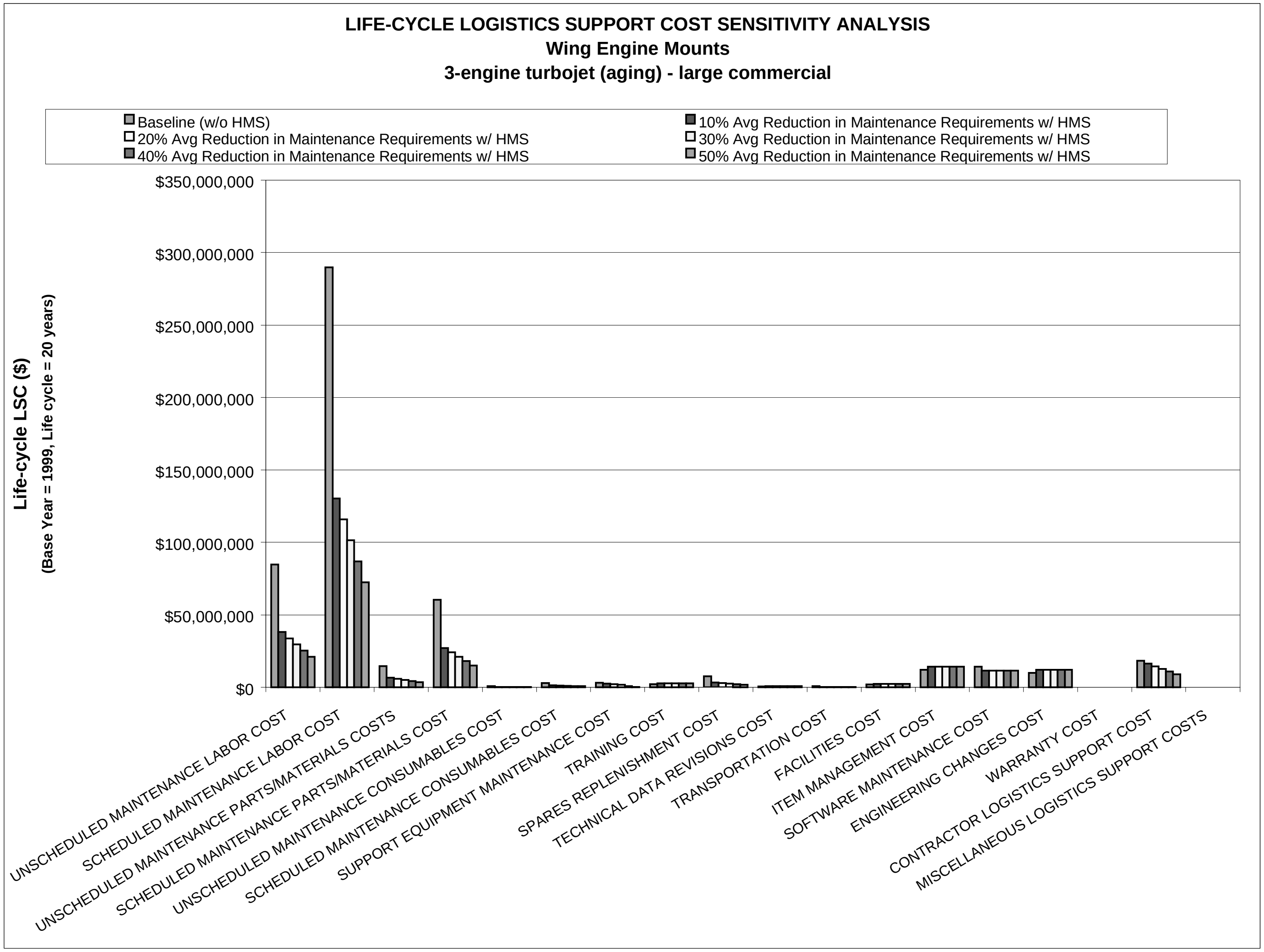


Figure 1-6: LSC Sensitivity Analysis, Wing Engine Mounts, 3-Engine Turbojet (aging)

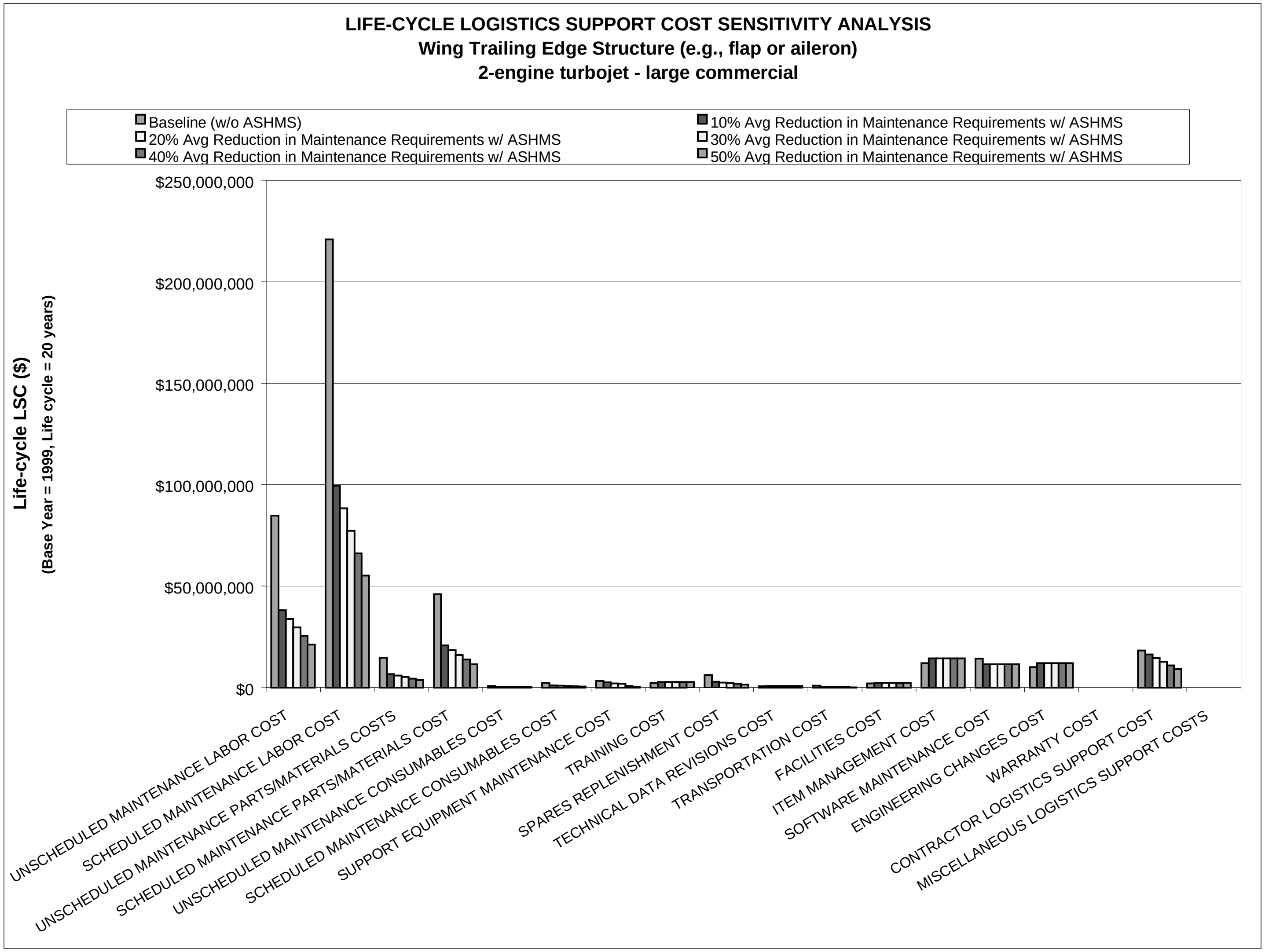


Figure 1-7: LSC Sensitivity Analysis, Wing Trailing Edge Structure, 2-Engine Turbojet

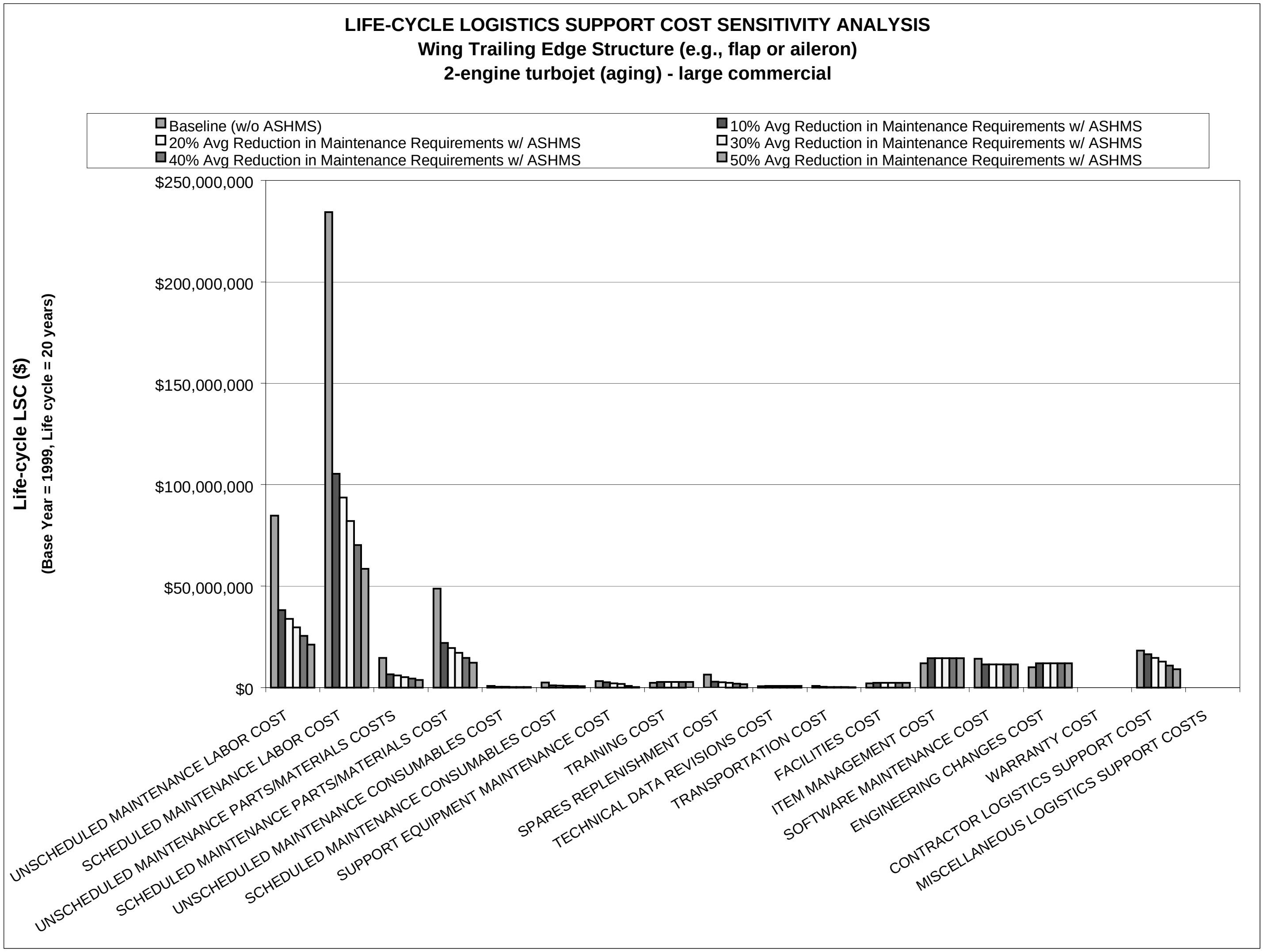


Figure 1-8: LSC Sensitivity Analysis, Wing Trailing Edge Structure, 2-Engine Turbojet (aging)

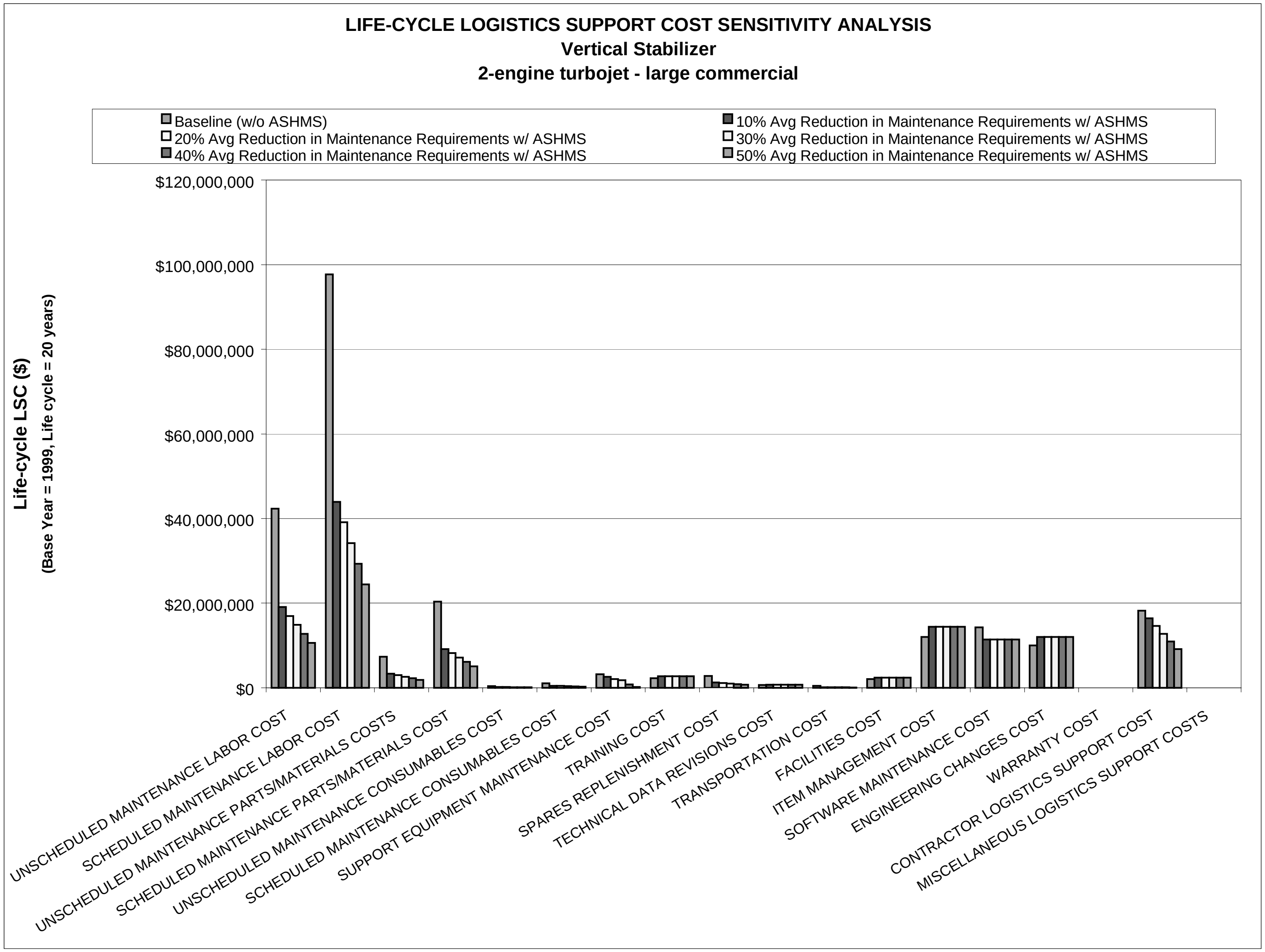


Figure1- 9: LSC Sensitivity Analysis, Vertical Stabilizer, 2-Engine Turbojet

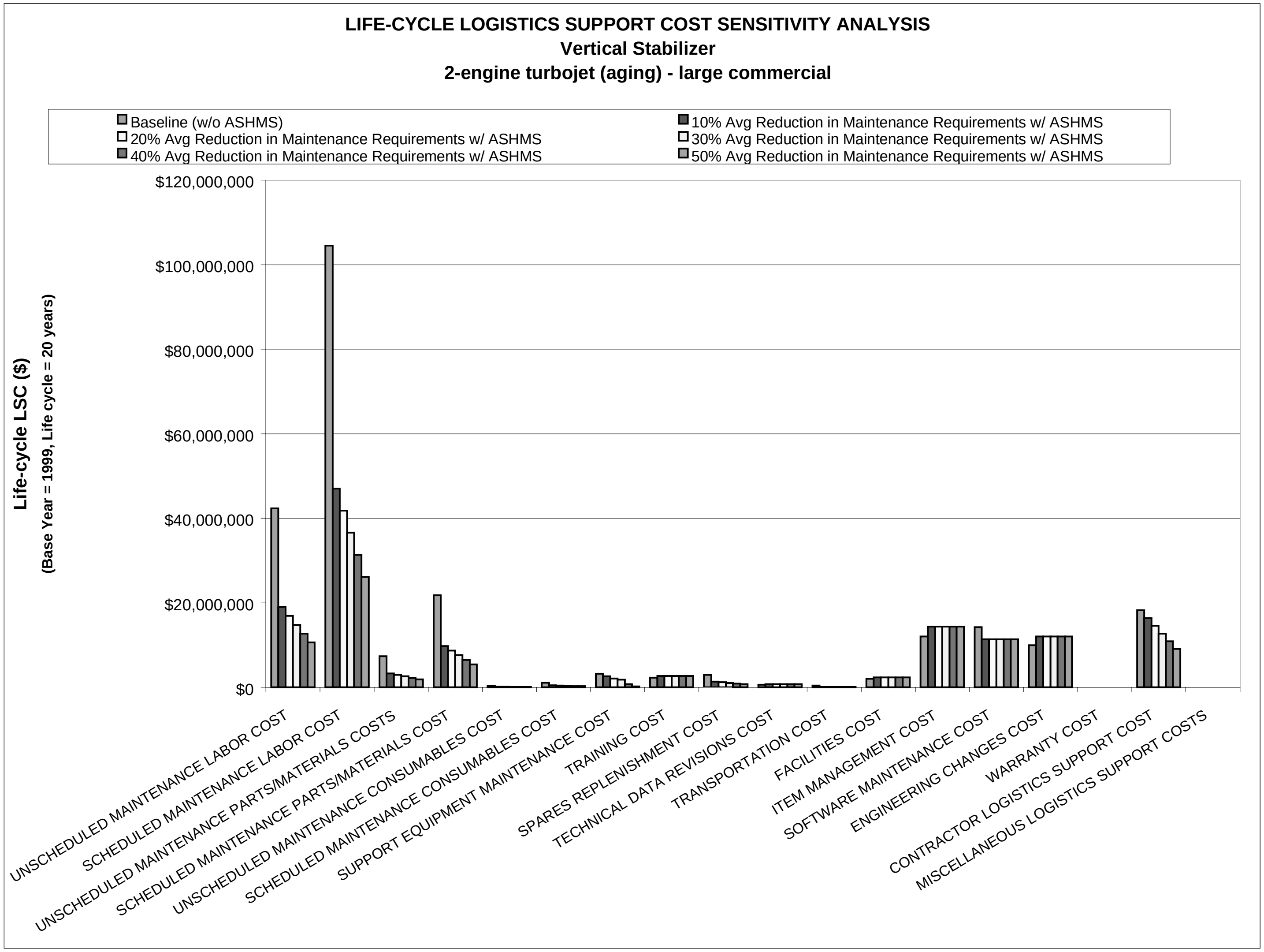


Figure 1-10: LSC Sensitivity Analysis, Vertical Stabilizer, 2-Engine Turbojet (aging)

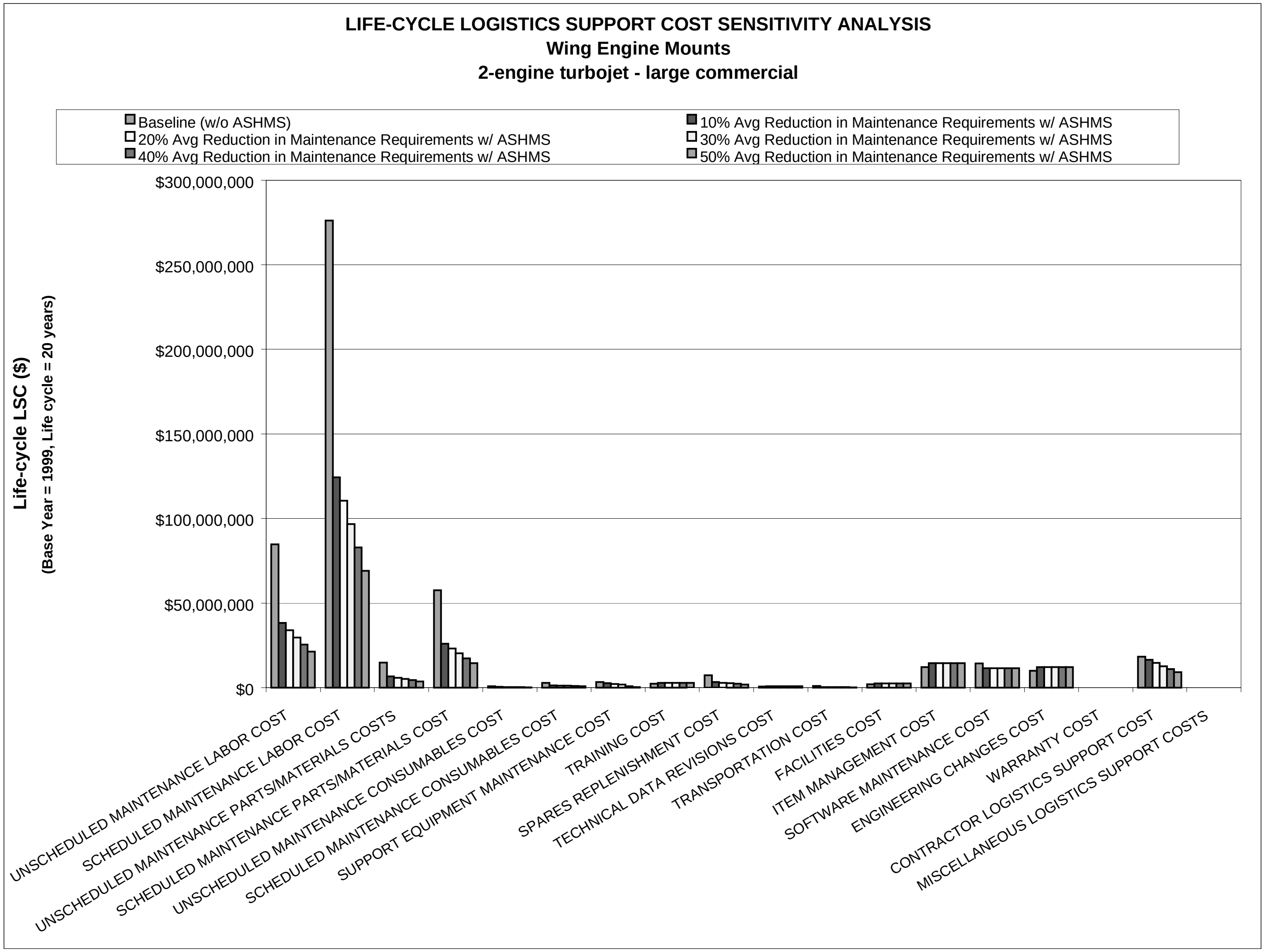


Figure 1-11: LSC Sensitivity Analysis, Wing Engine Mounts, 2-Engine Turbojet

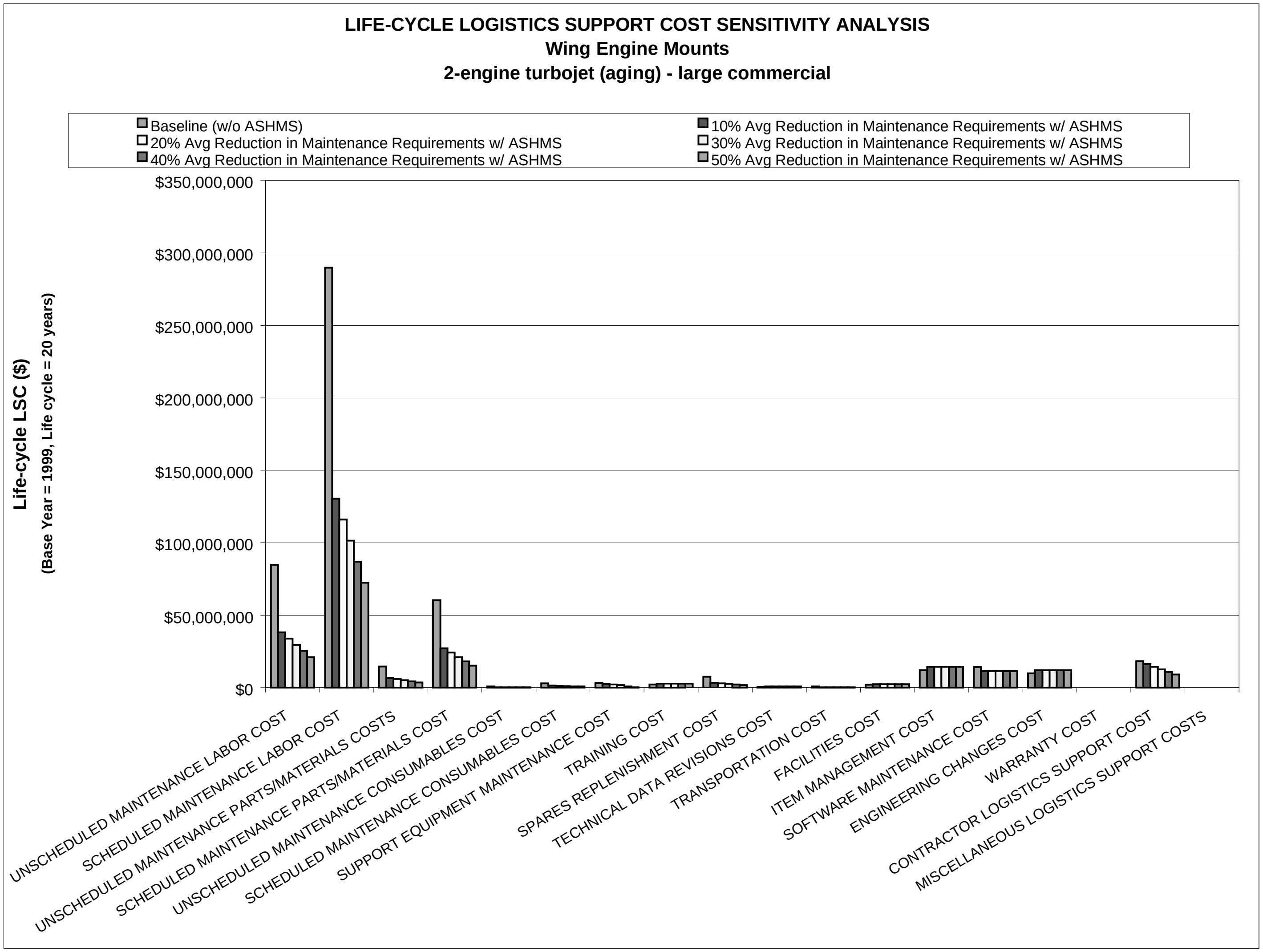


Figure 1-12: LSC Sensitivity Analysis, Wing Engine Mounts, 2-Engine Turbojet (aging)

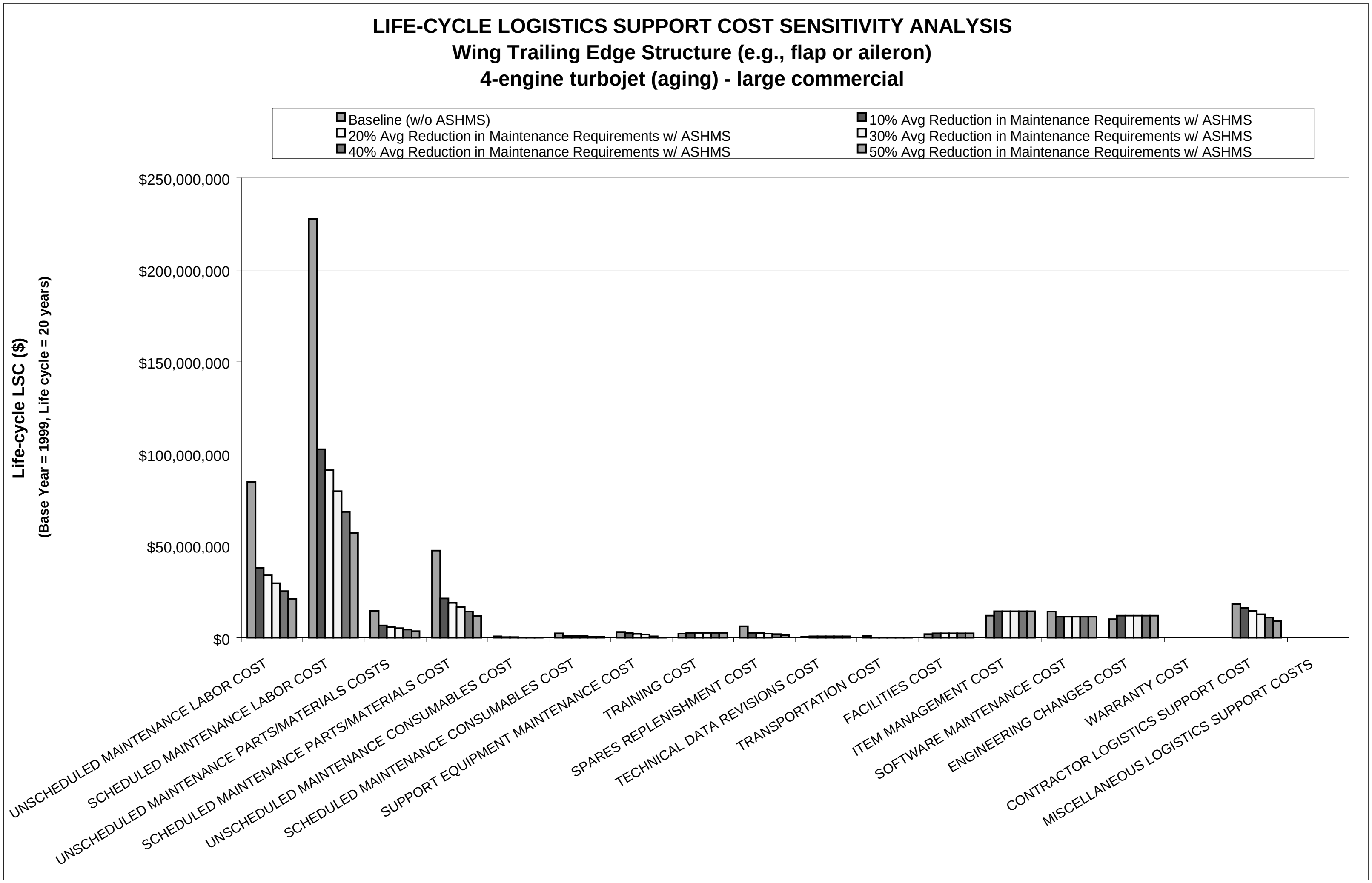


Figure 1-13: LSC Sensitivity Analysis, Wing Trailing Edge Structure, 4-Engine Turbojet (aging)

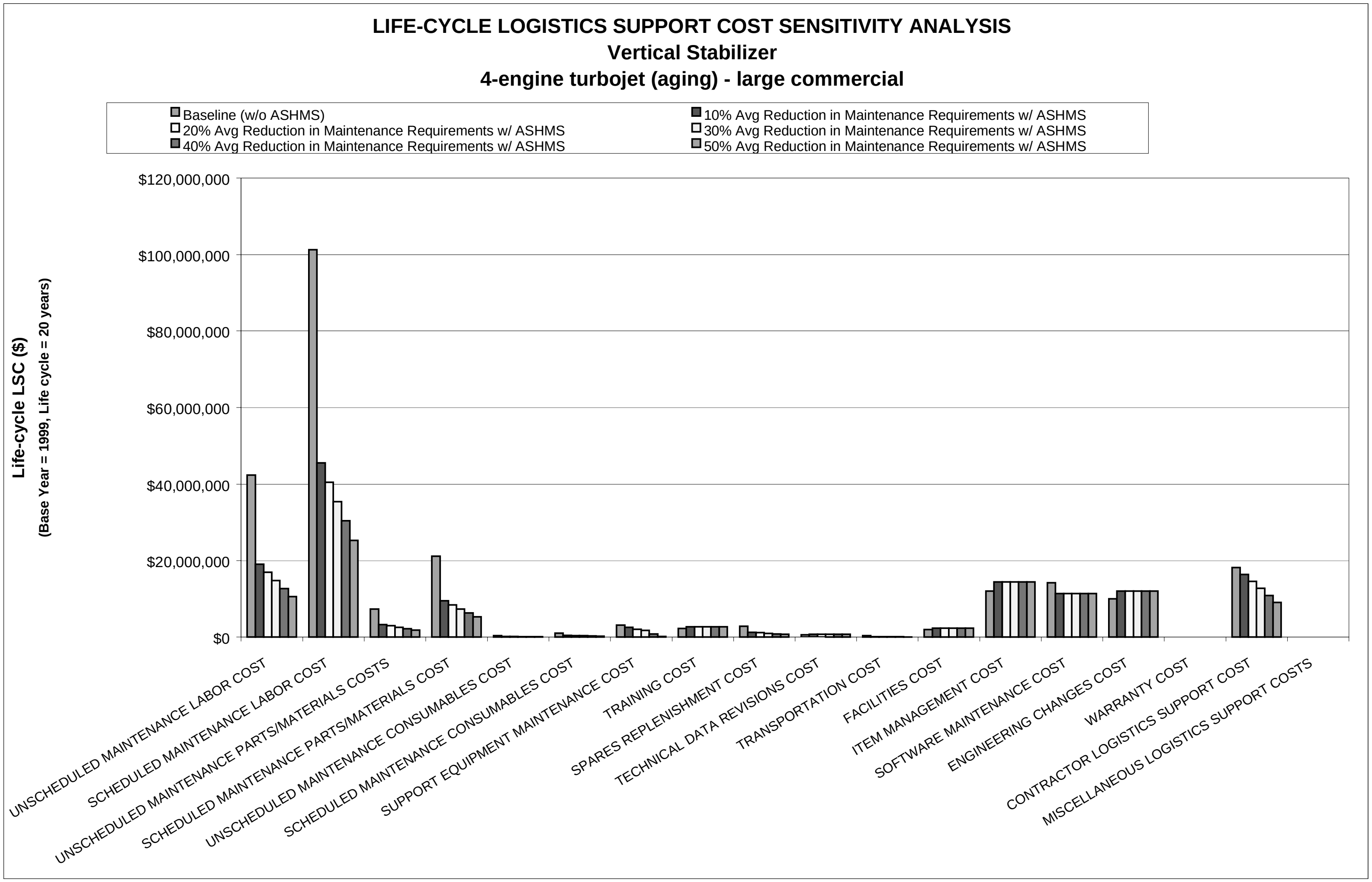


Figure 1-14: LSC Sensitivity Analysis, Vertical Stabilizer, 4-Engine Turbojet (aging)

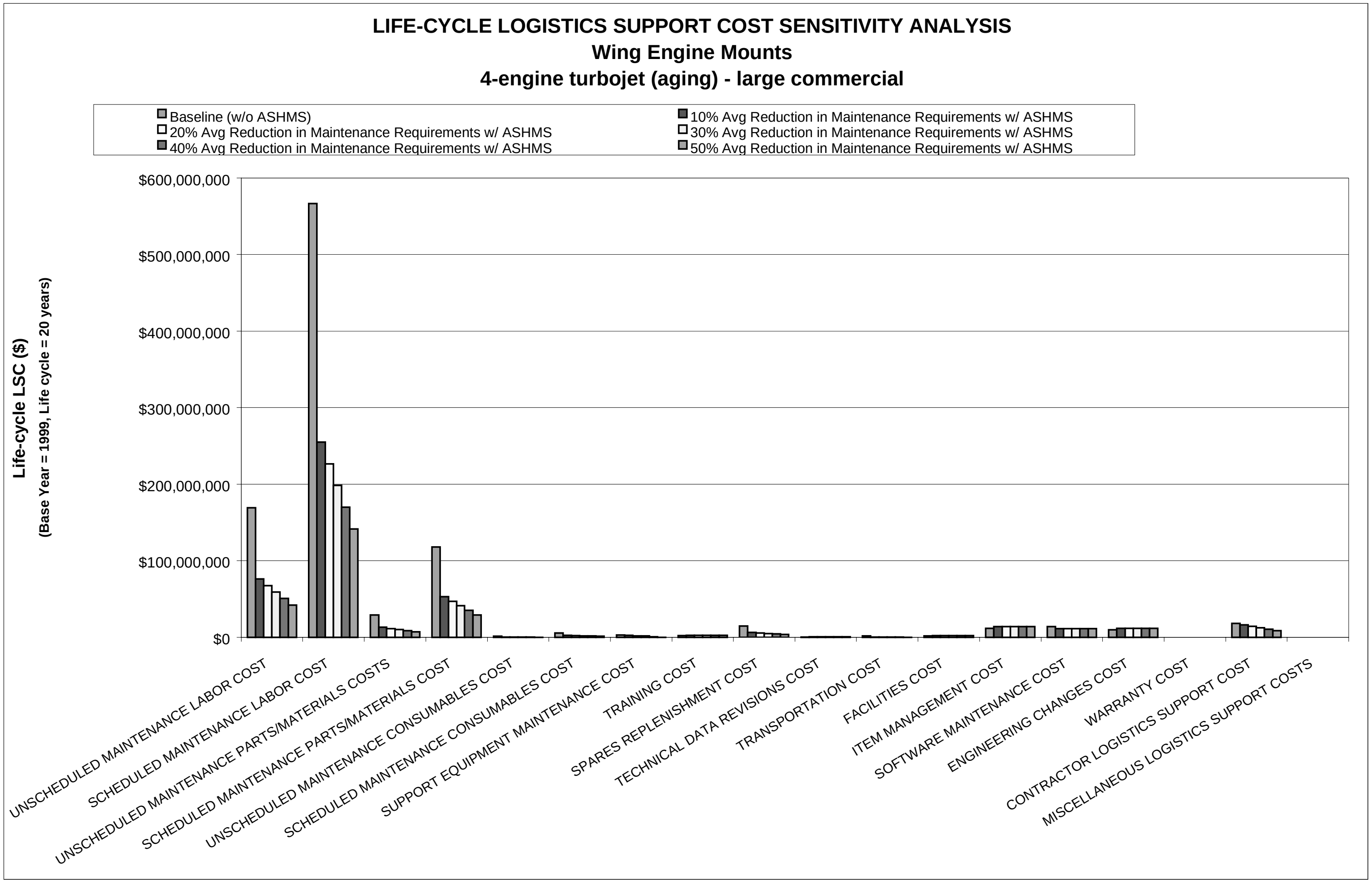


Figure 1-15: LSC Sensitivity Analysis, Wing Engine Mounts, 4-Engine Turbojet (aging)

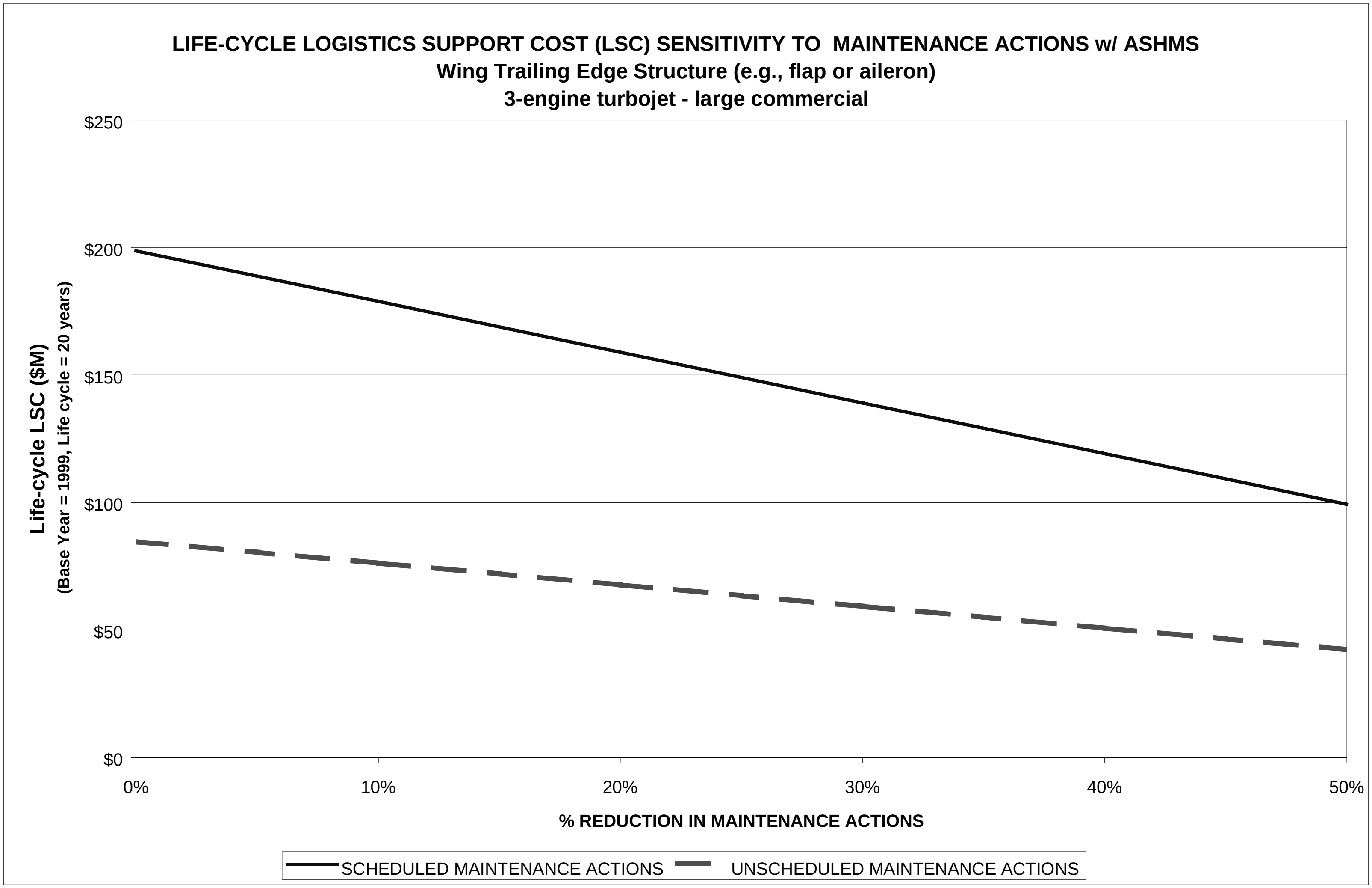


Figure 2-1: LSC Sensitivity to Maintenance Actions, Wing Trailing Edge Structure, 3-Engine Turbojet

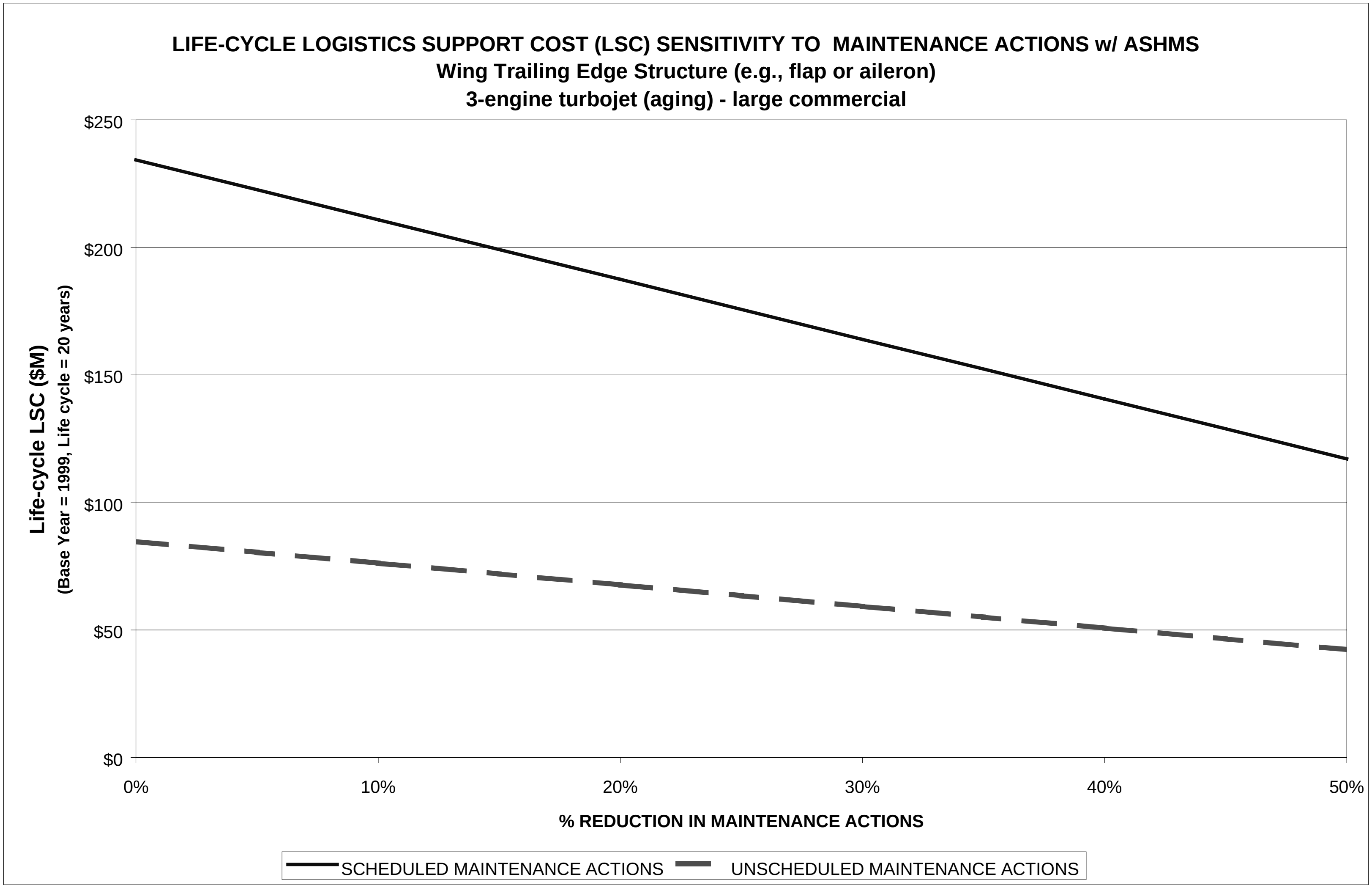


Figure 2-2: LSC Sensitivity to Maintenance Actions, Wing Trailing Edge Structure, 3-Engine Turbojet (aging)

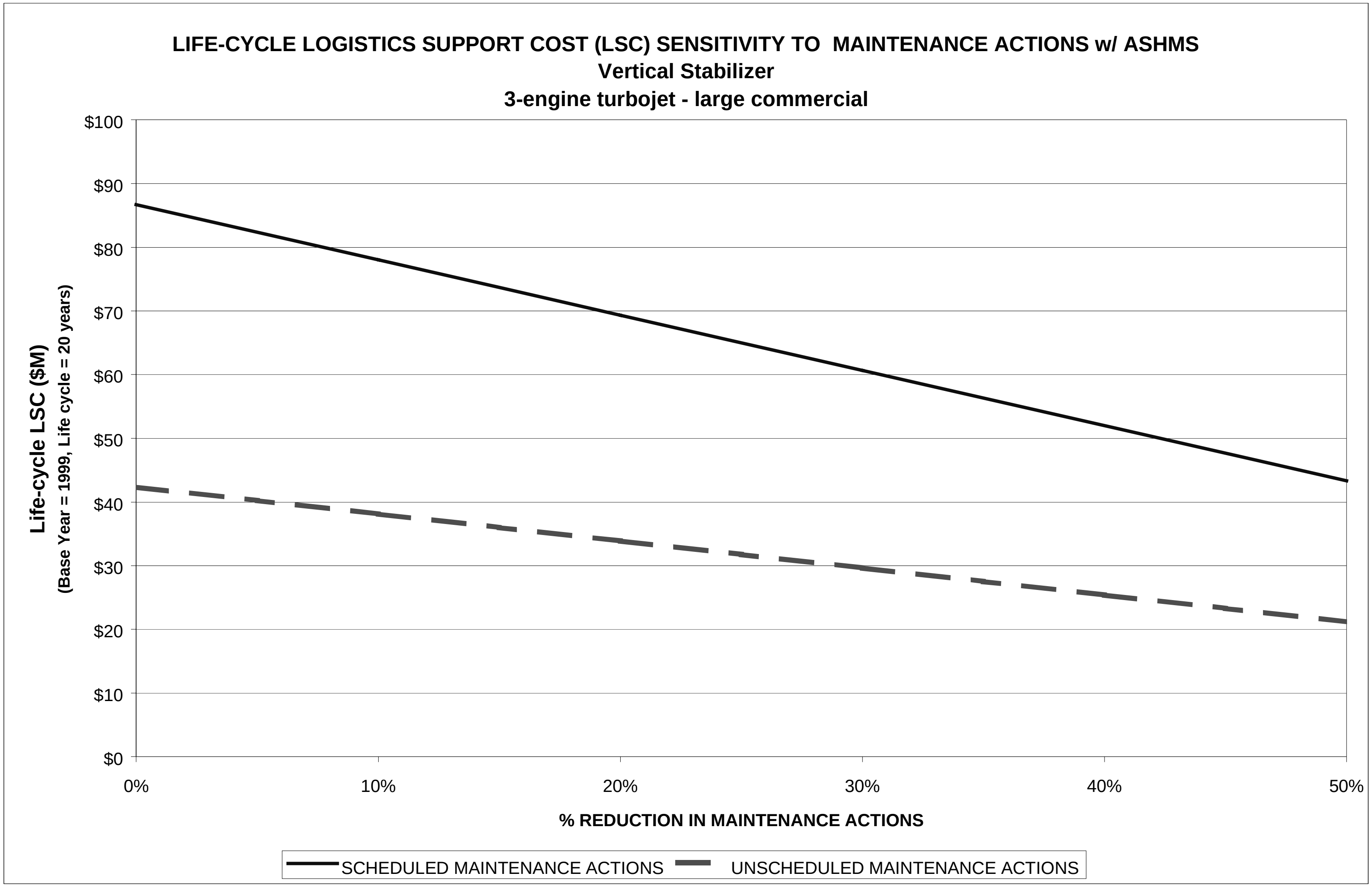


Figure 2-3: LSC Sensitivity to Maintenance Actions, Vertical Stabilizer, 3-Engine Turbojet

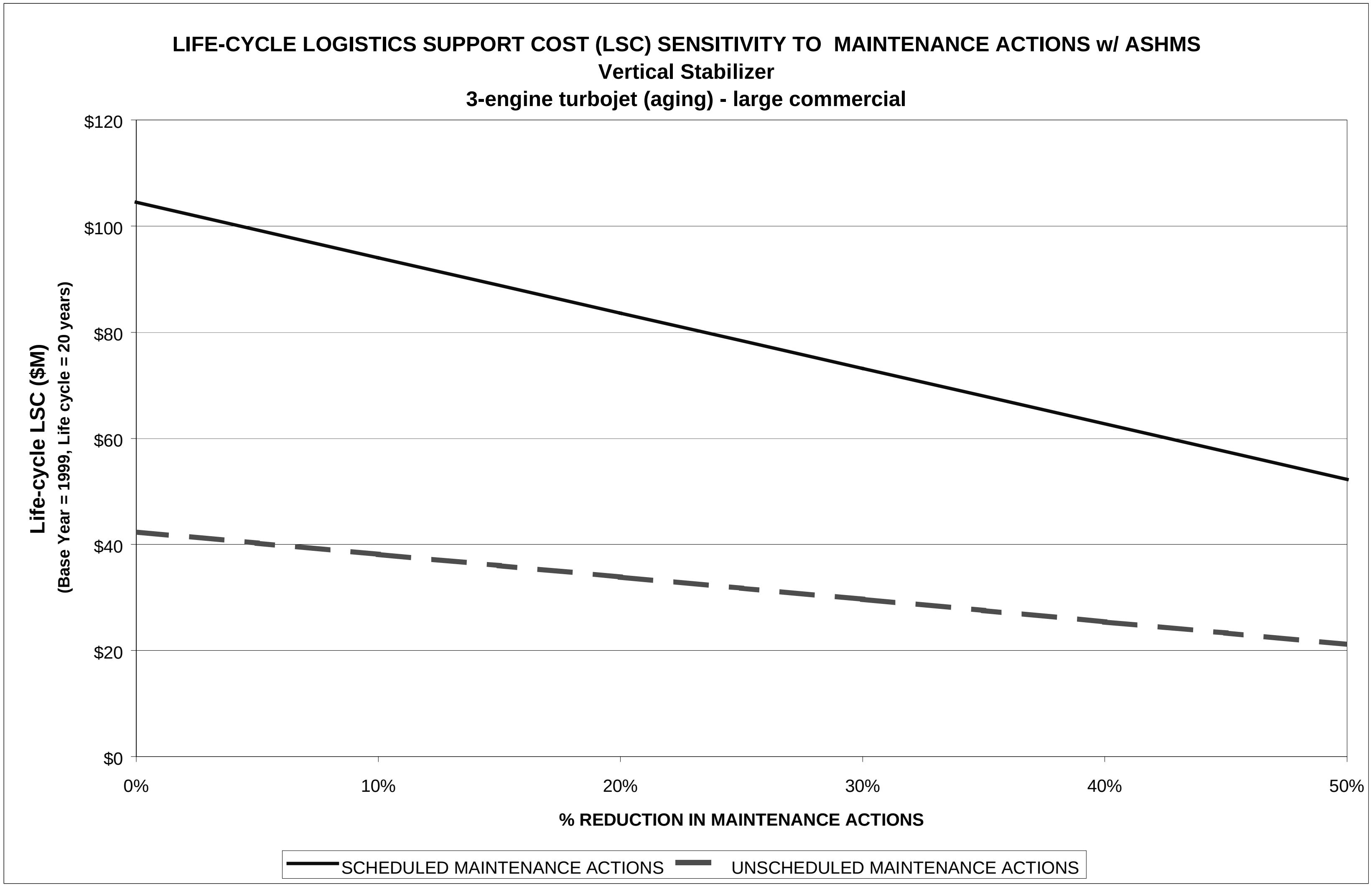


Figure 2-4: LSC Sensitivity to Maintenance Actions, Vertical Stabilizer, 3-Engine Turbojet (aging)

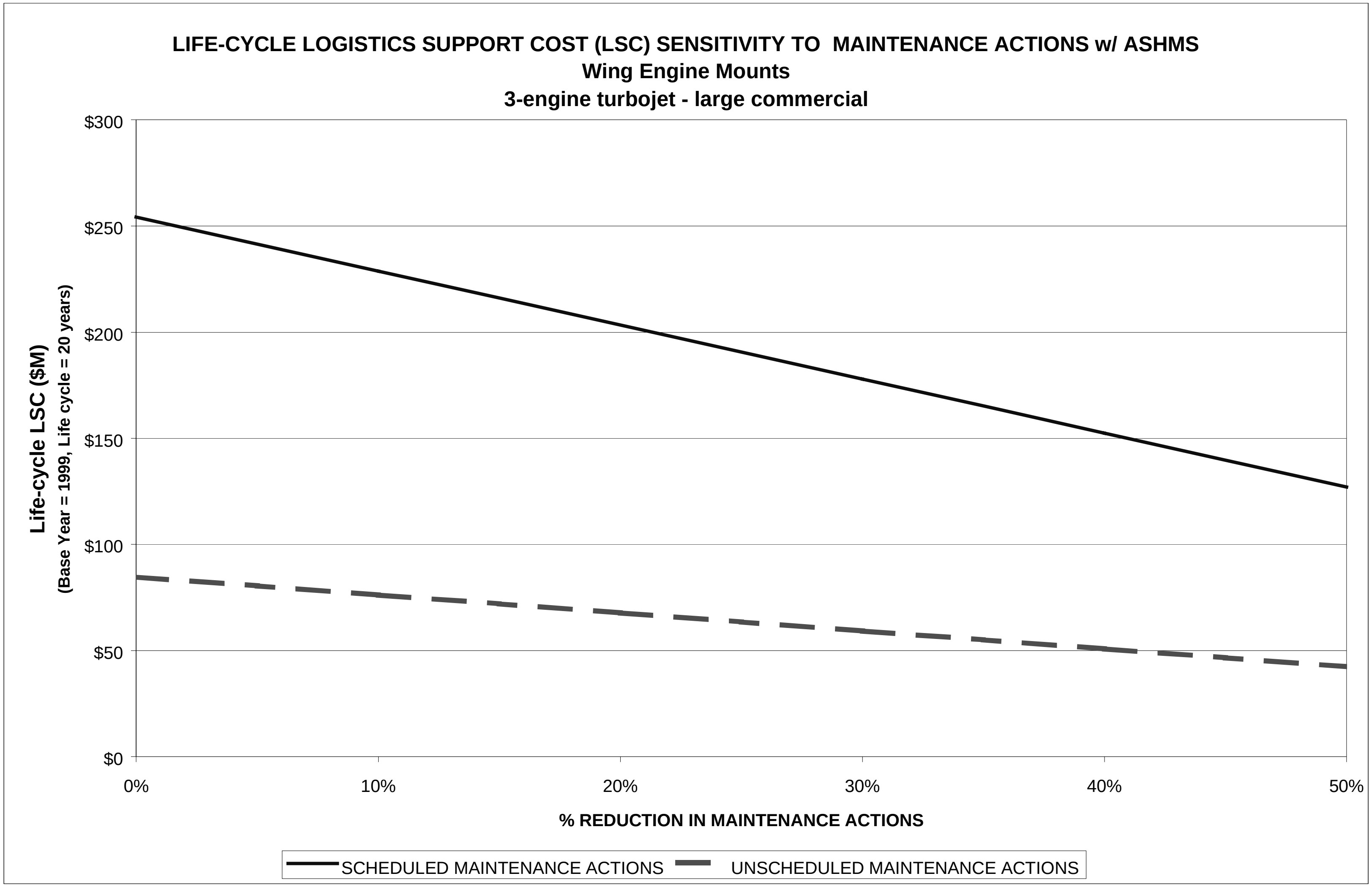


Figure 2-5: LSC Sensitivity to Maintenance Actions, Wing Engine Mounts, 3-Engine Turbojet

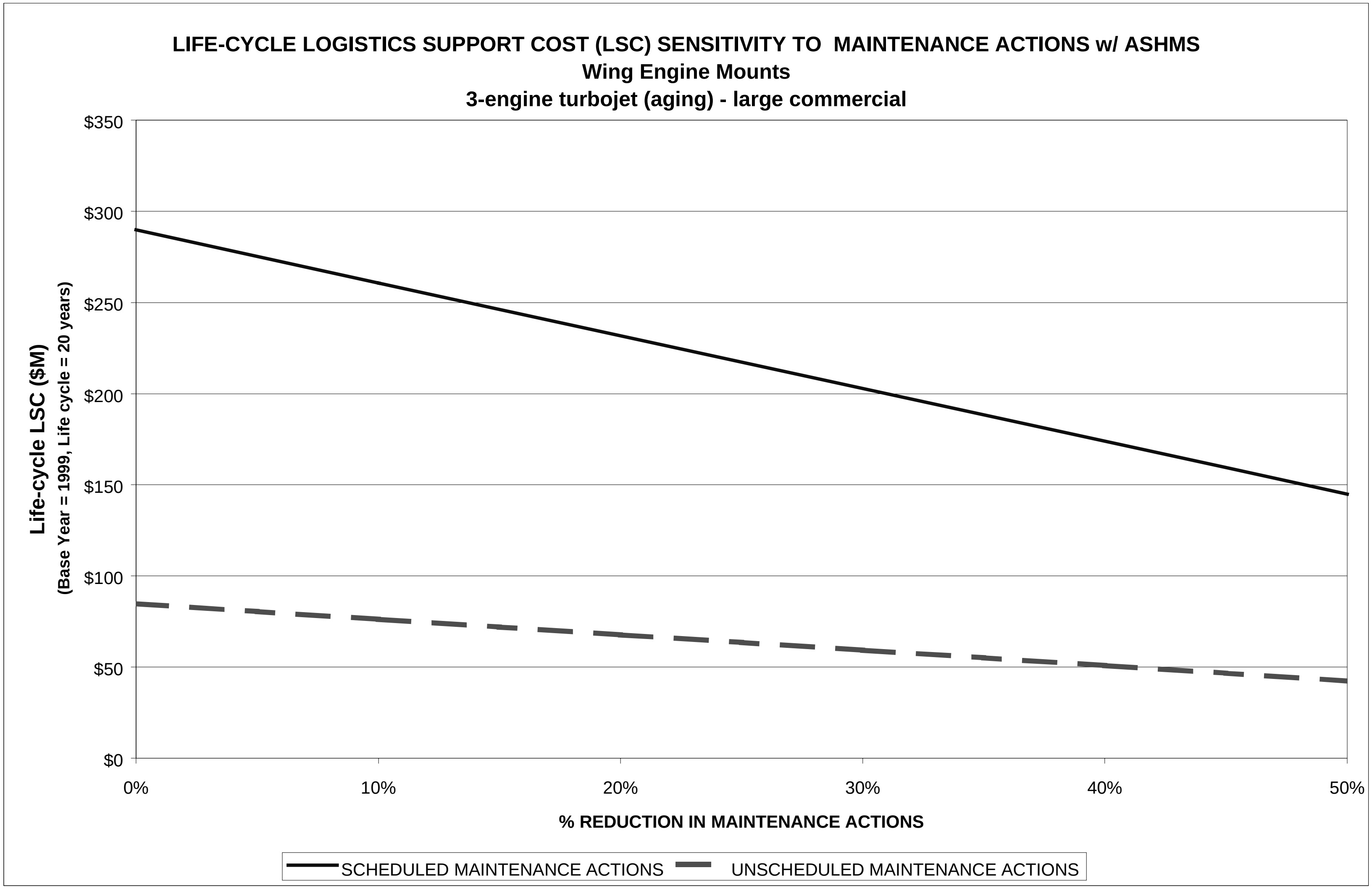


Figure 2-6: LSC Sensitivity to Maintenance Actions, Wing Engine Mounts, 3-Engine Turbojet (aging)

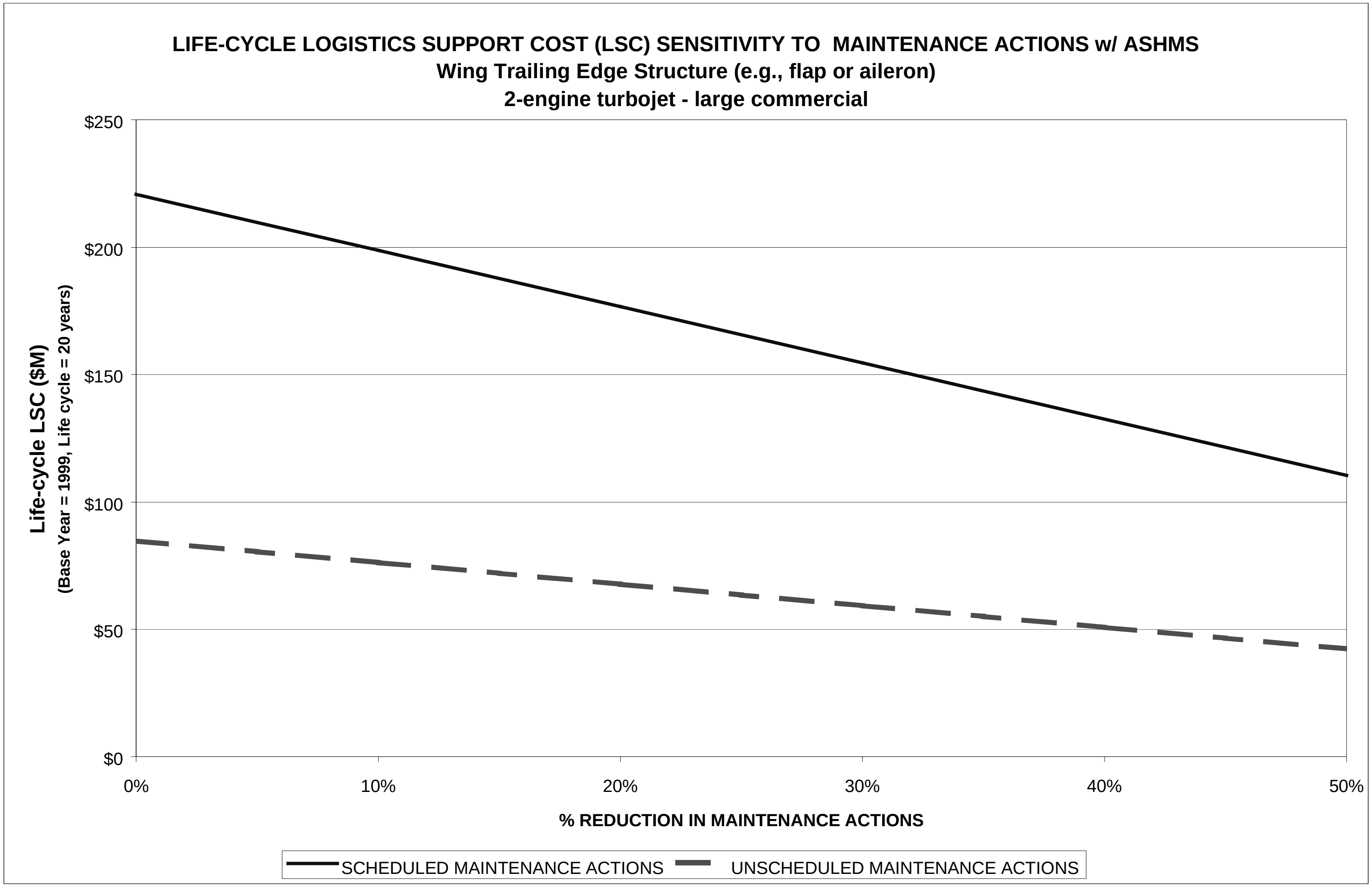


Figure 2-7: LSC Sensitivity to Maintenance Actions, Wing Trailing Edge Structure, 2-Engine Turbojet

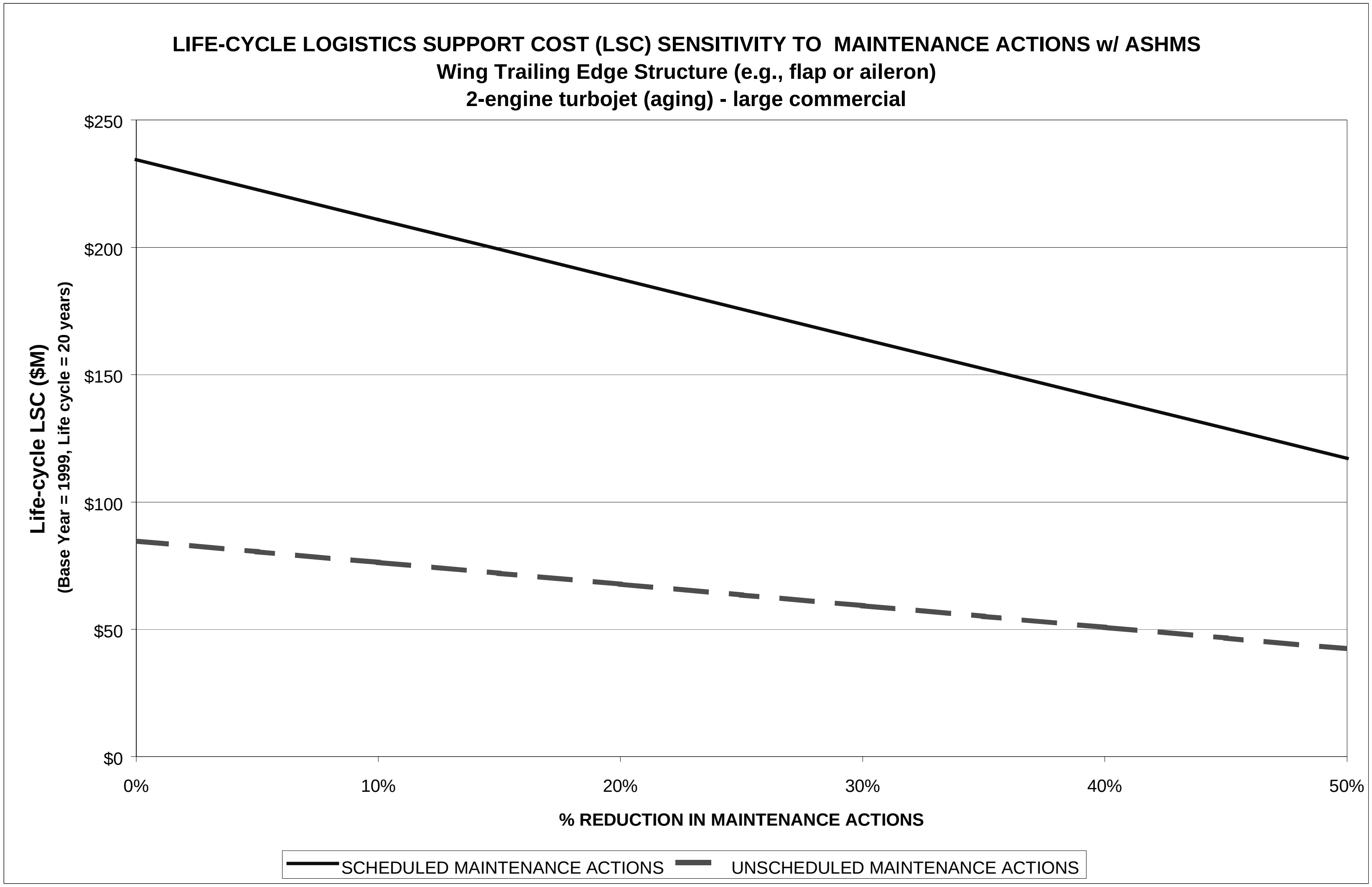


Figure 2-8: LSC Sensitivity to Maintenance Actions, Wing Trailing Edge Structure, 2-Engine Turbojet (aging)

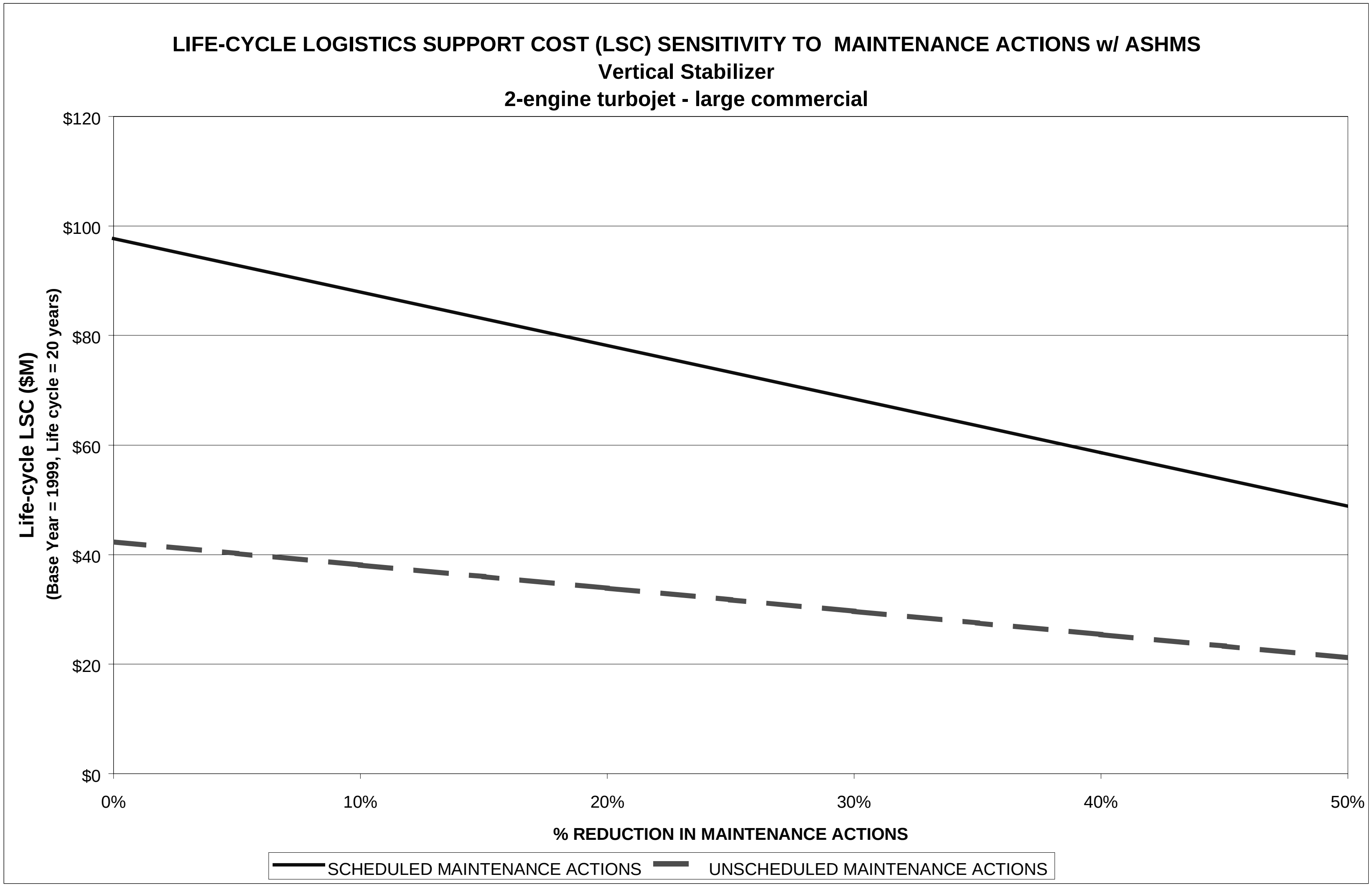


Figure 2-9: LSC Sensitivity to Maintenance Actions, Vertical Stabilizer, 2-Engine Turbojet

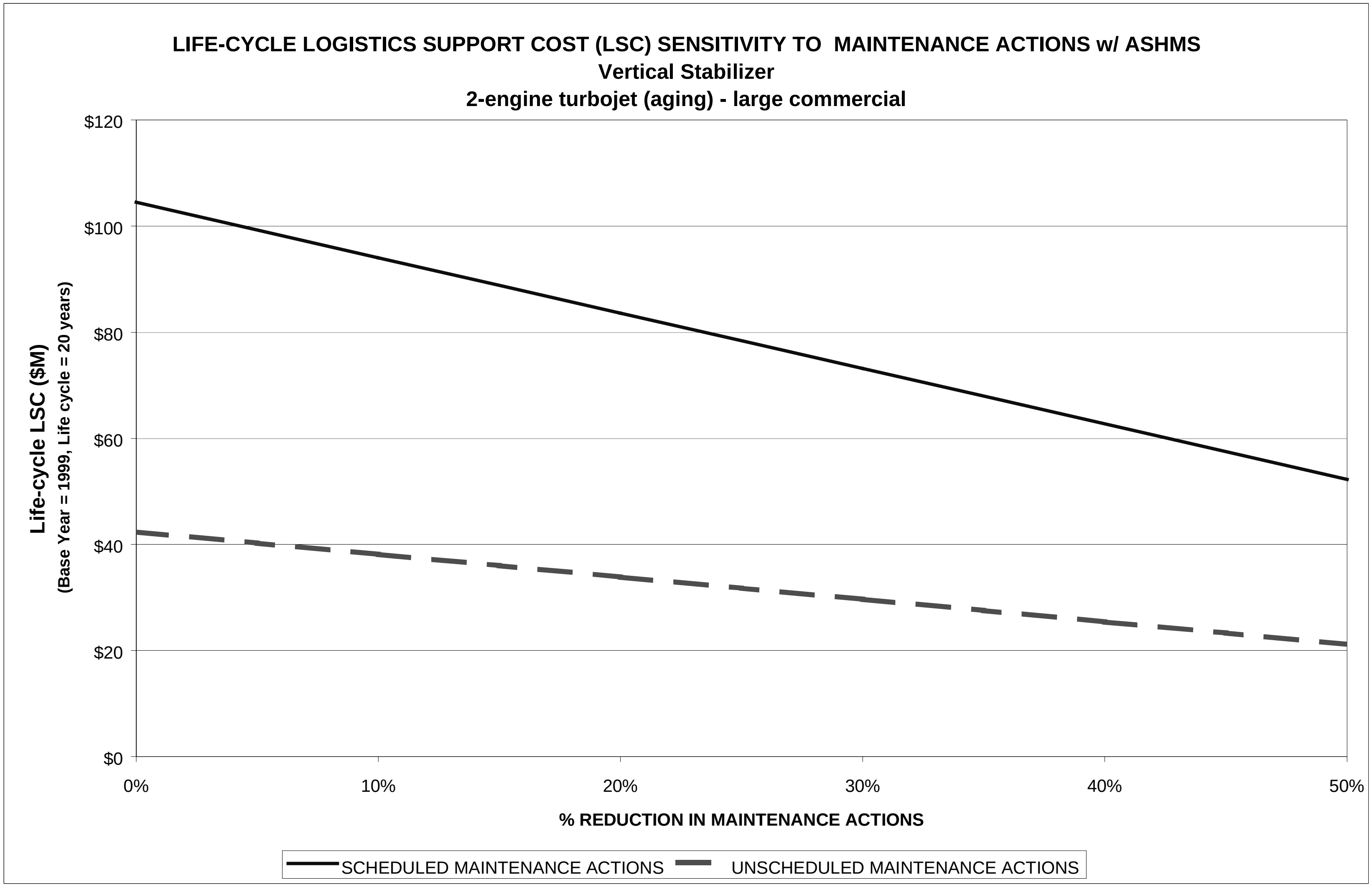


Figure 2-10: LSC Sensitivity to Maintenance Actions, Vertical Stabilizer, 2-Engine Turbojet (aging)

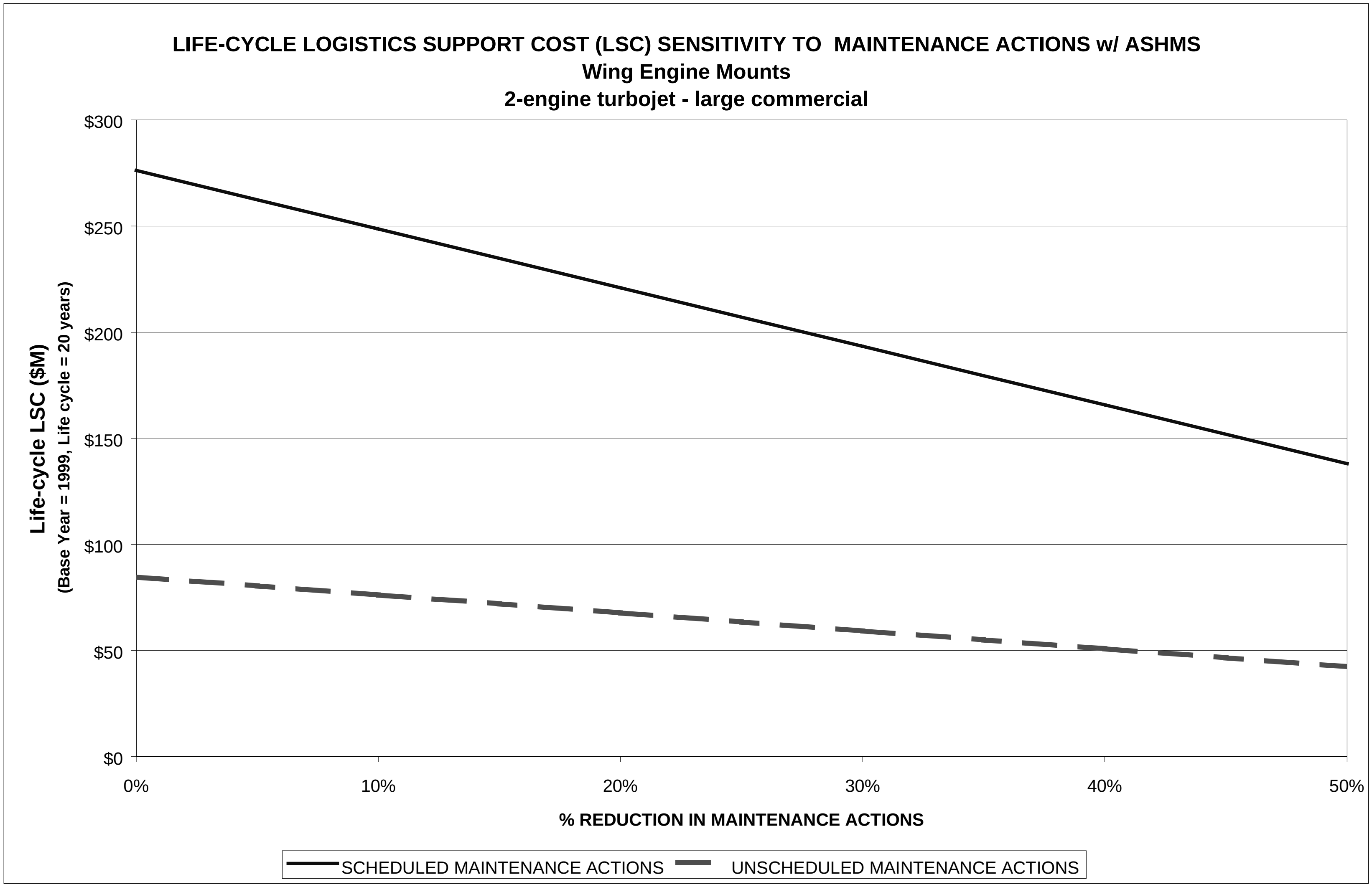


Figure 2-11: LSC Sensitivity to Maintenance Actions, Wing Engine Mounts, 2-Engine Turbojet

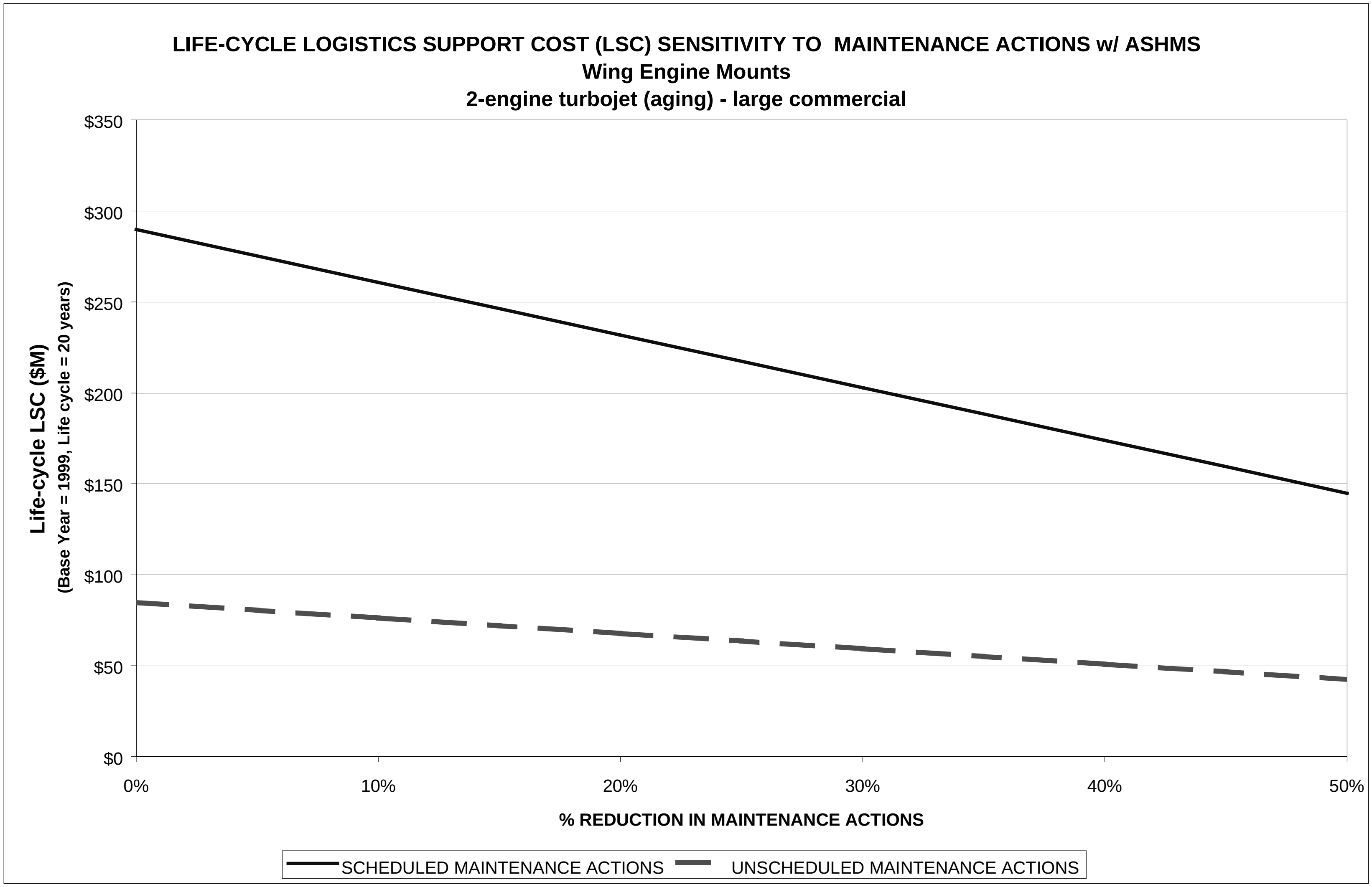


Figure 2-12: LSC Sensitivity to Maintenance Actions, Wing Engine Mounts, 2-Engine Turbojet (aging)

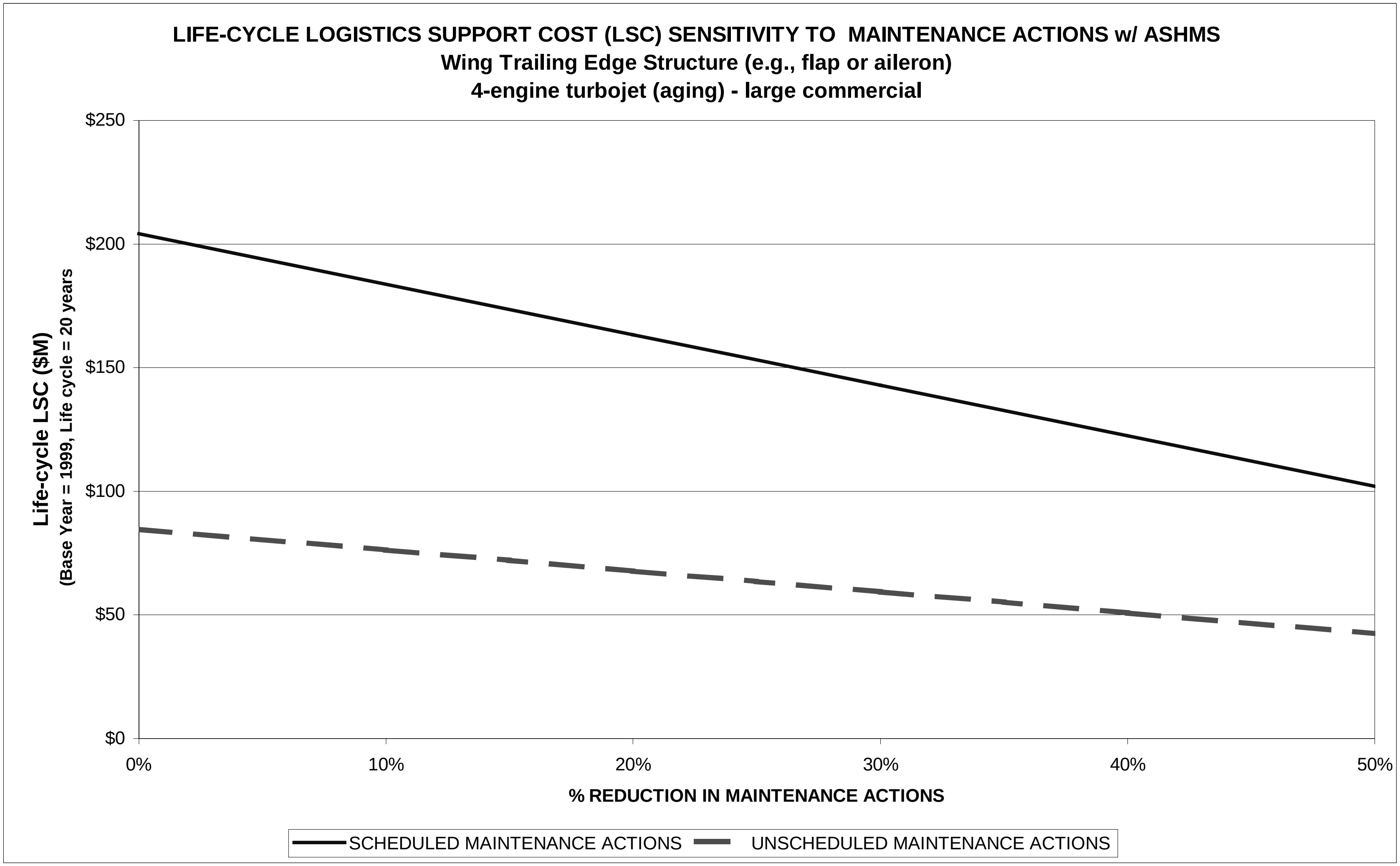


Figure 2-13: LSC Sensitivity to Maintenance Actions, Wing Trailing Edge Structure, 4-Engine Turbojet (aging)

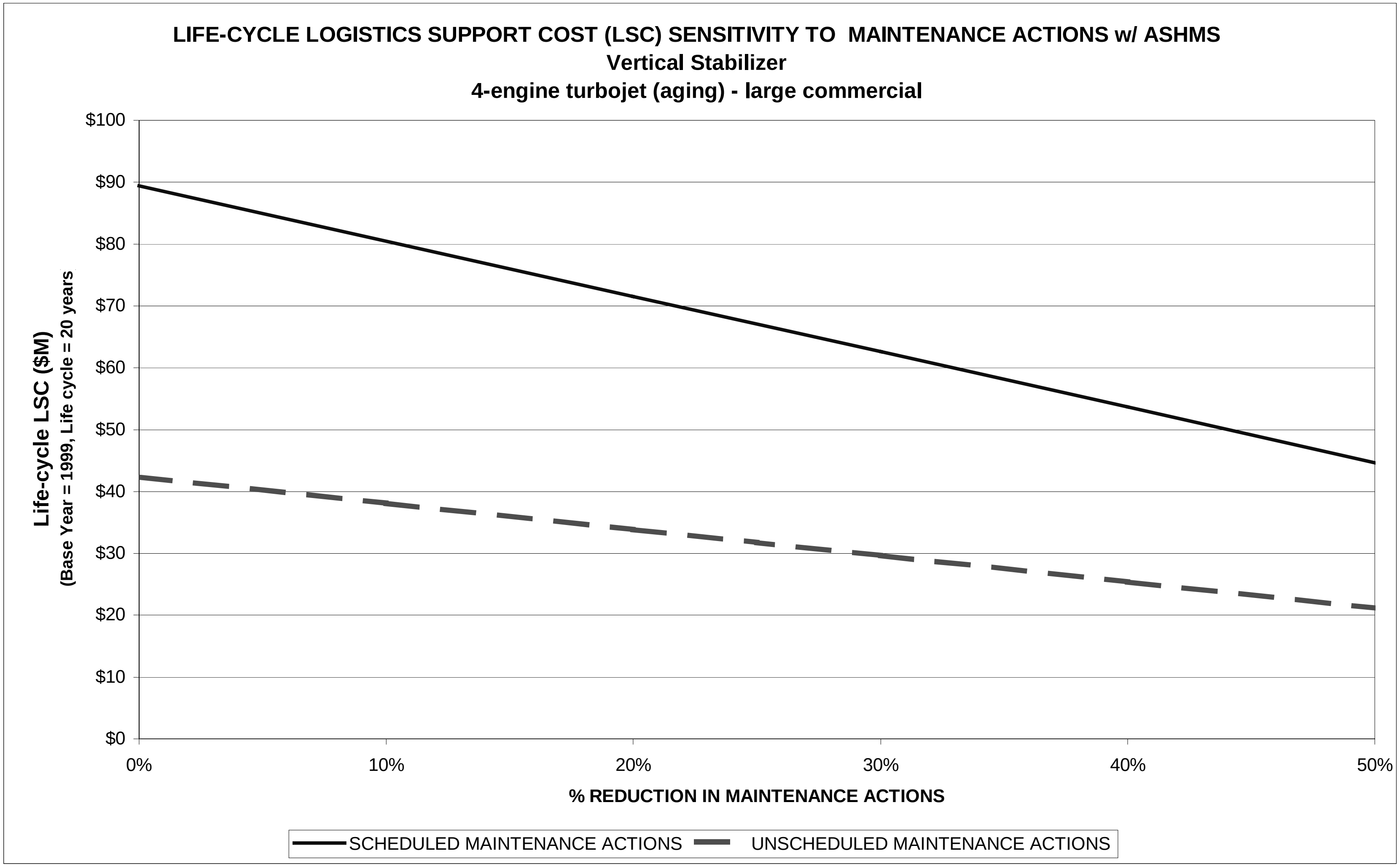


Figure 2-14: LSC Sensitivity to Maintenance Actions, Vertical Stabilizer, 4-Engine Turbojet (aging)

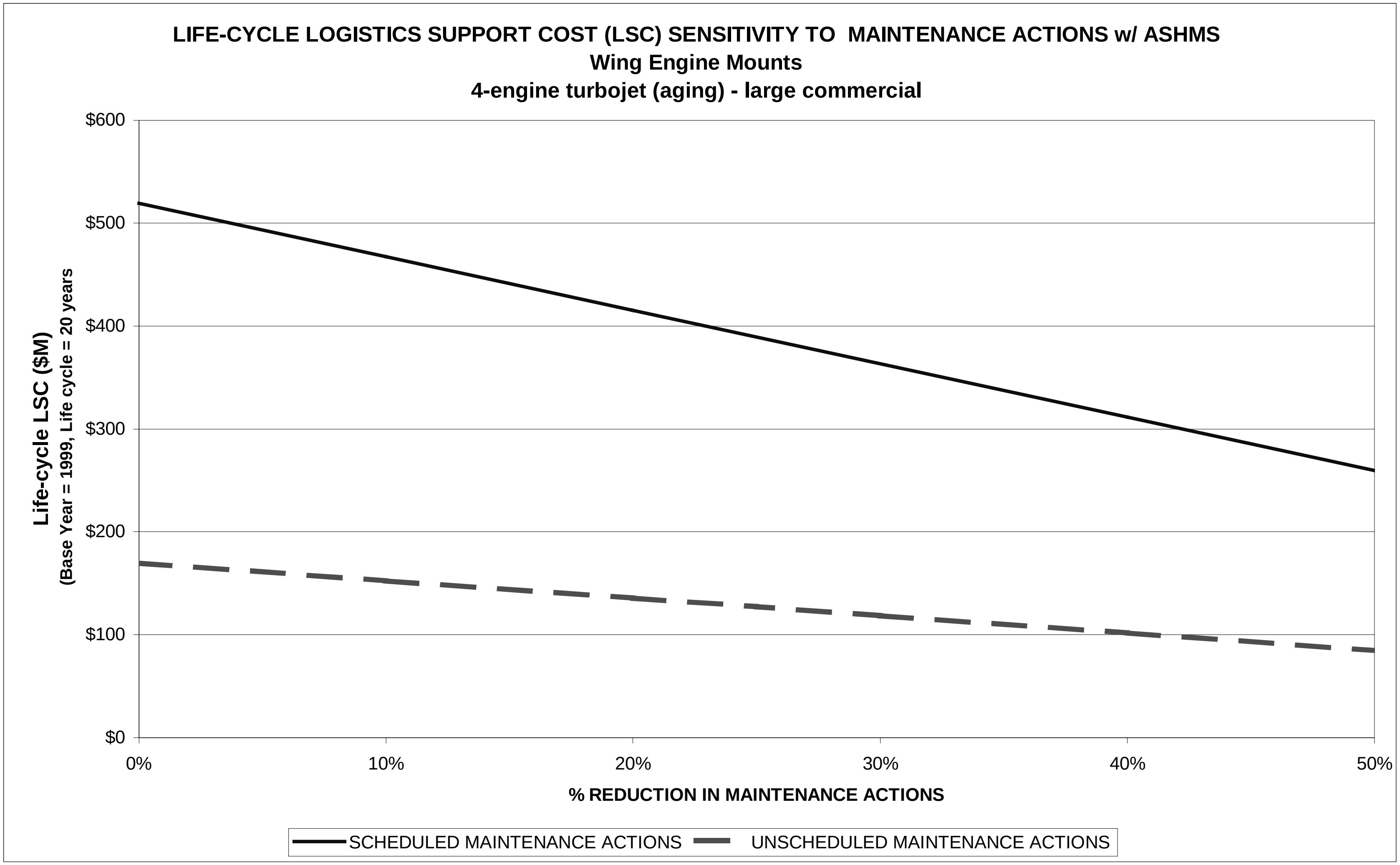


Figure 2-15: LSC Sensitivity to Maintenance Actions, Wing Engine Mounts, 4-Engine Turbojet (aging)

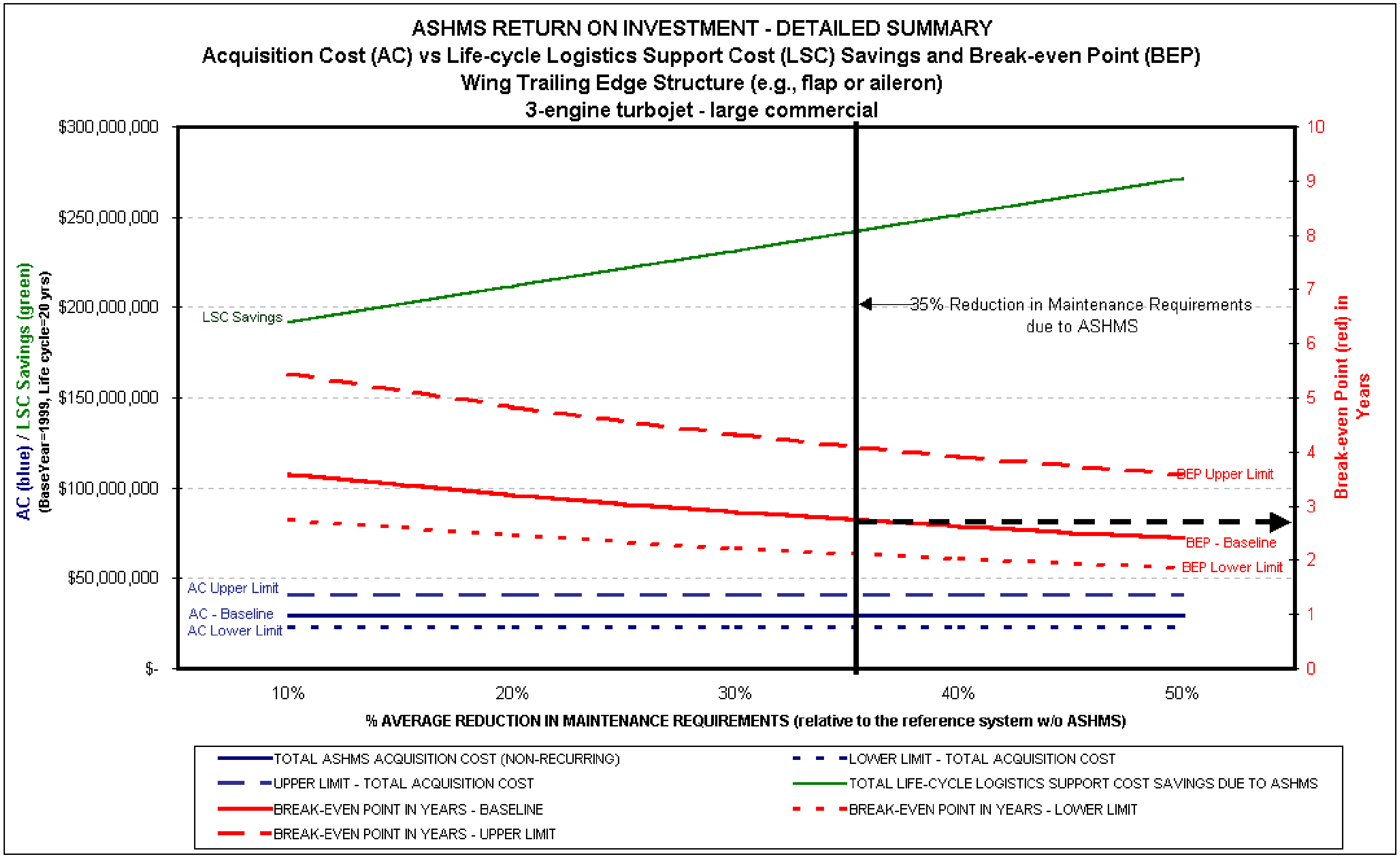


Figure 3-1: Return on Investment Detailed Summary, Wing Trailing Edge Structure, 3-Engine Turbojet

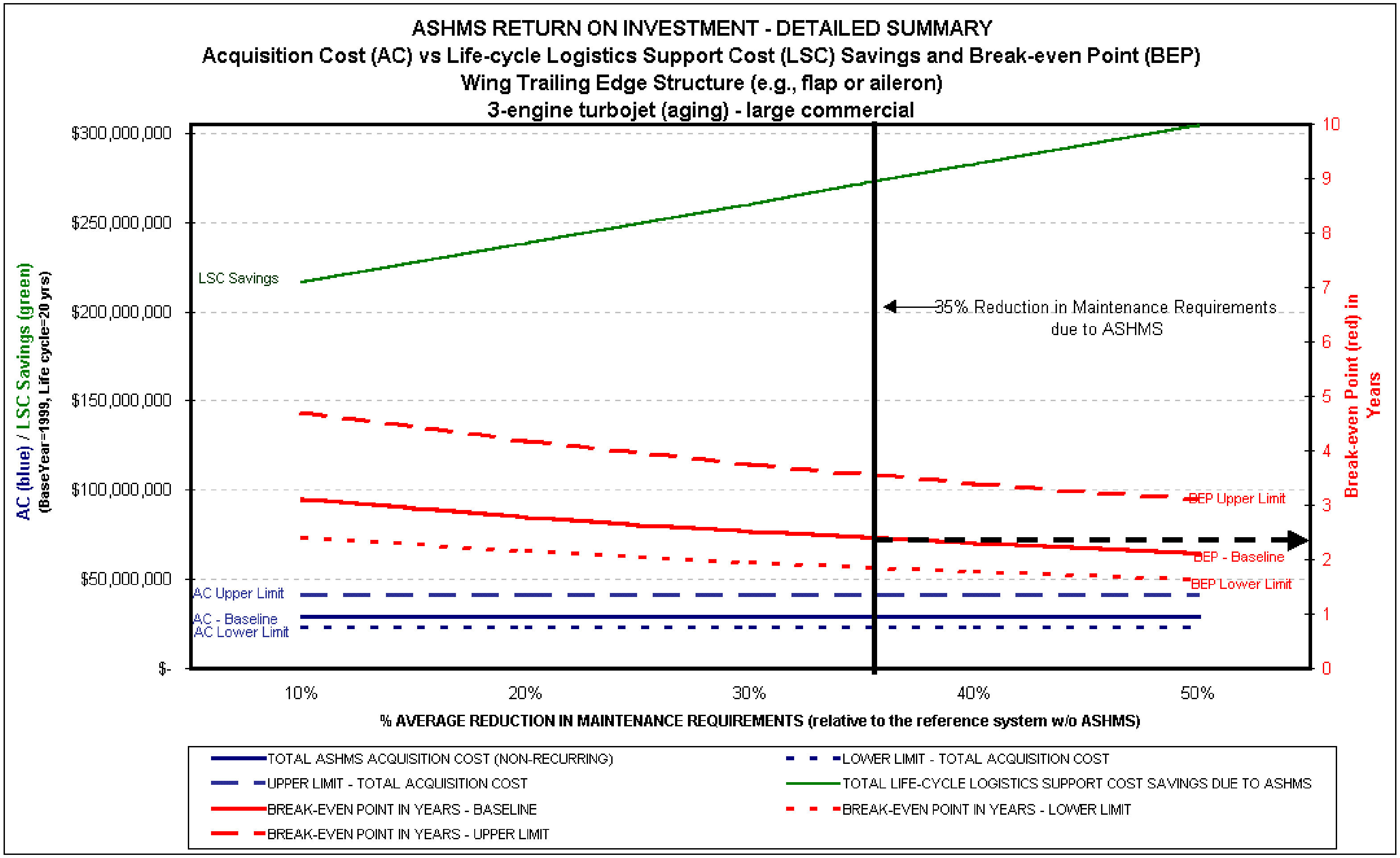


Figure 3-2: Return on Investment Detailed Summary, Wing Trailing Edge Structure, 3-Engine Turbojet (aging)

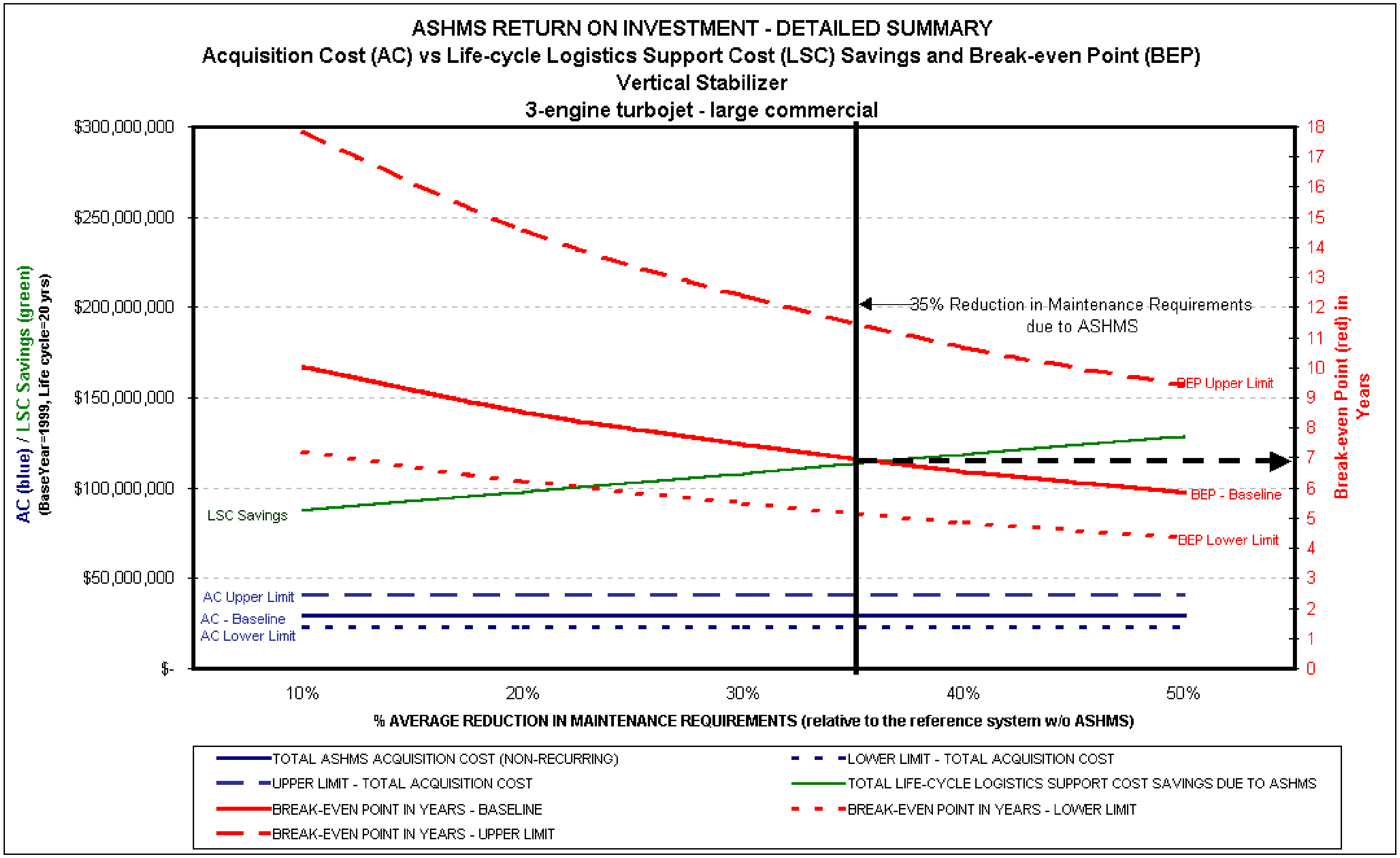


Figure 3-3: Return on Investment Detailed Summary, Vertical Stabilizer, 3-Engine Turbojet

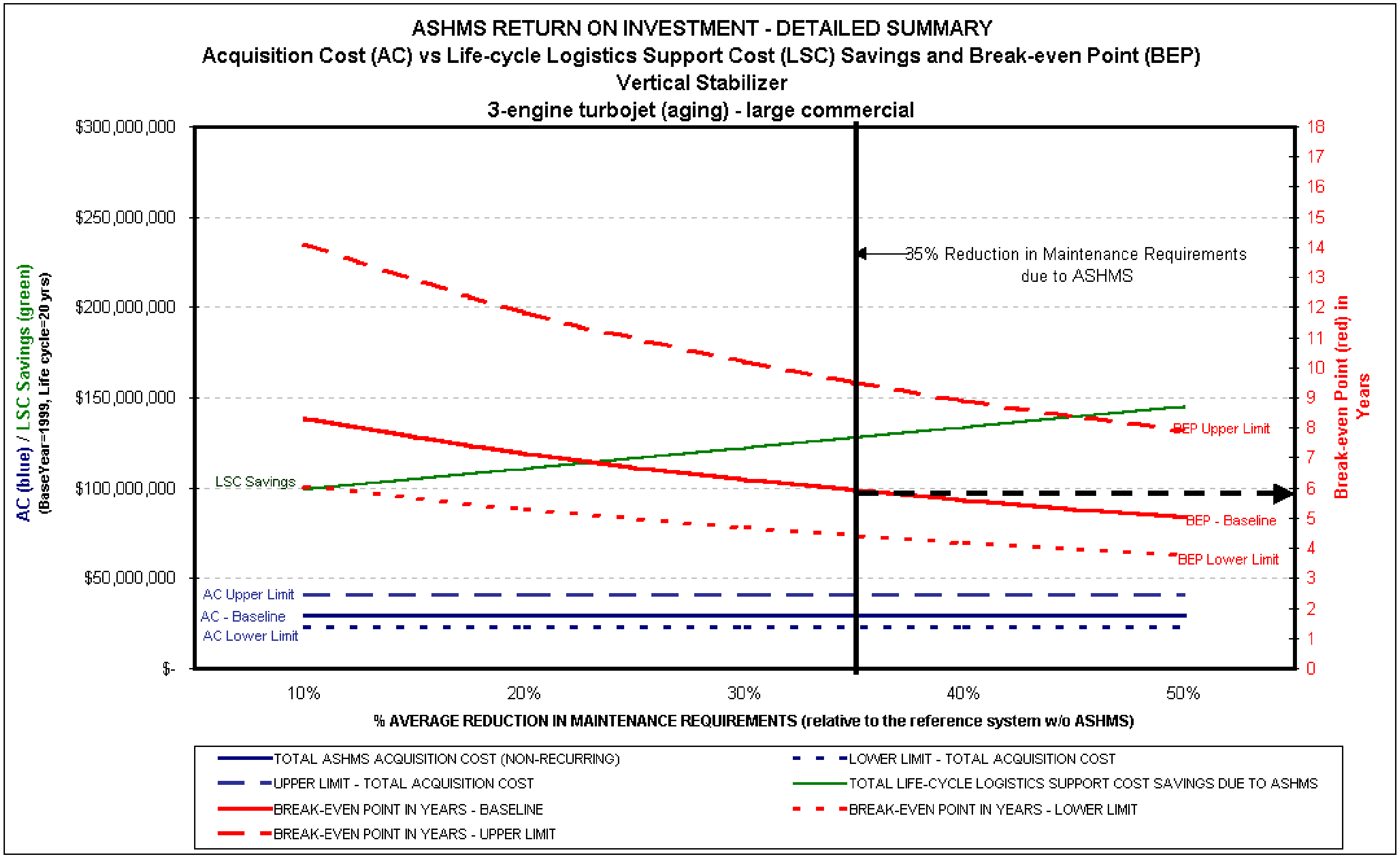


Figure 3-4: Return on Investment Detailed Summary, Vertical Stabilizer, 3-Engine Turbojet (aging)

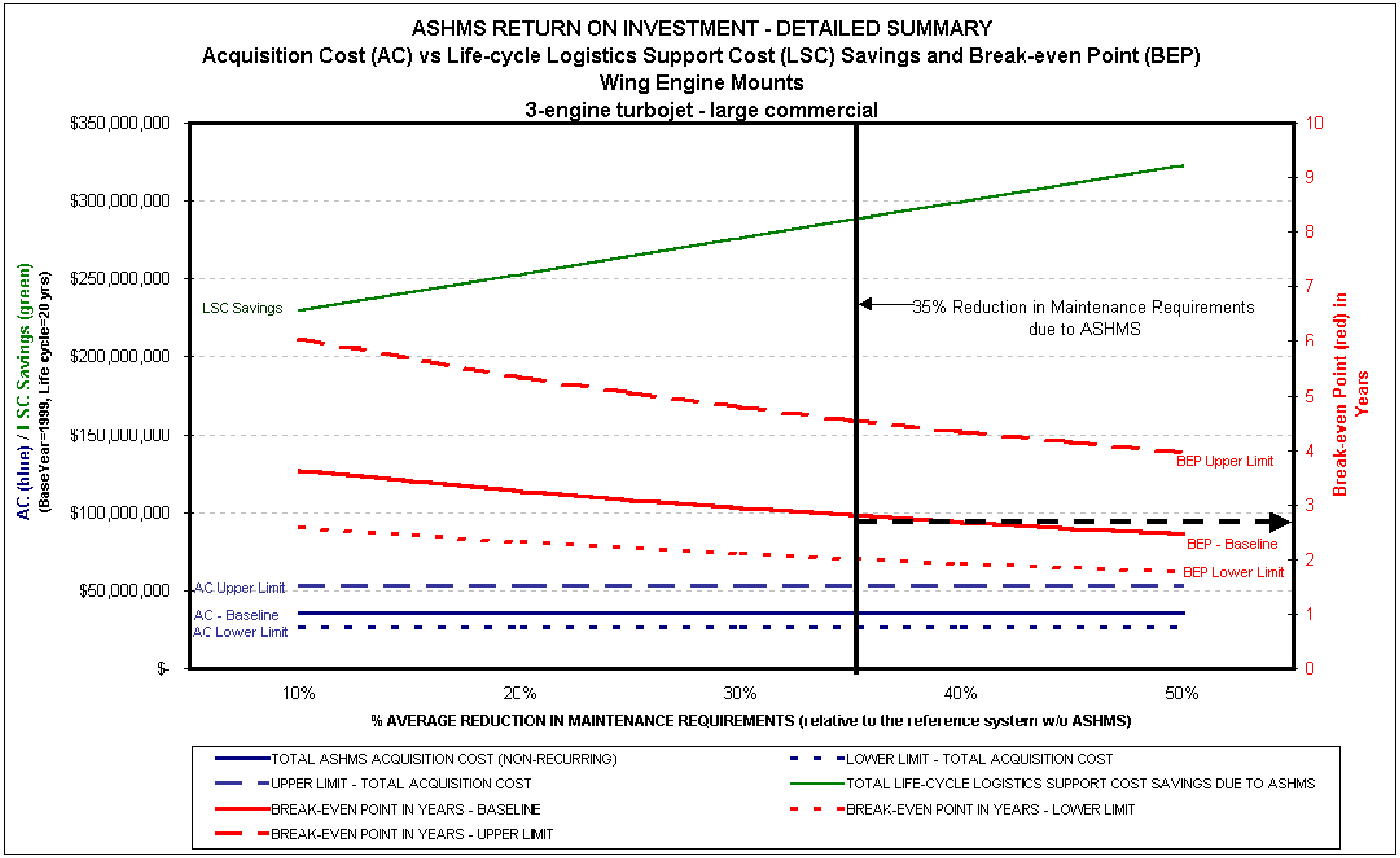


Figure 3-5: Return on Investment Detailed Summary, Wing Engine Mounts, 3-Engine Turbojet

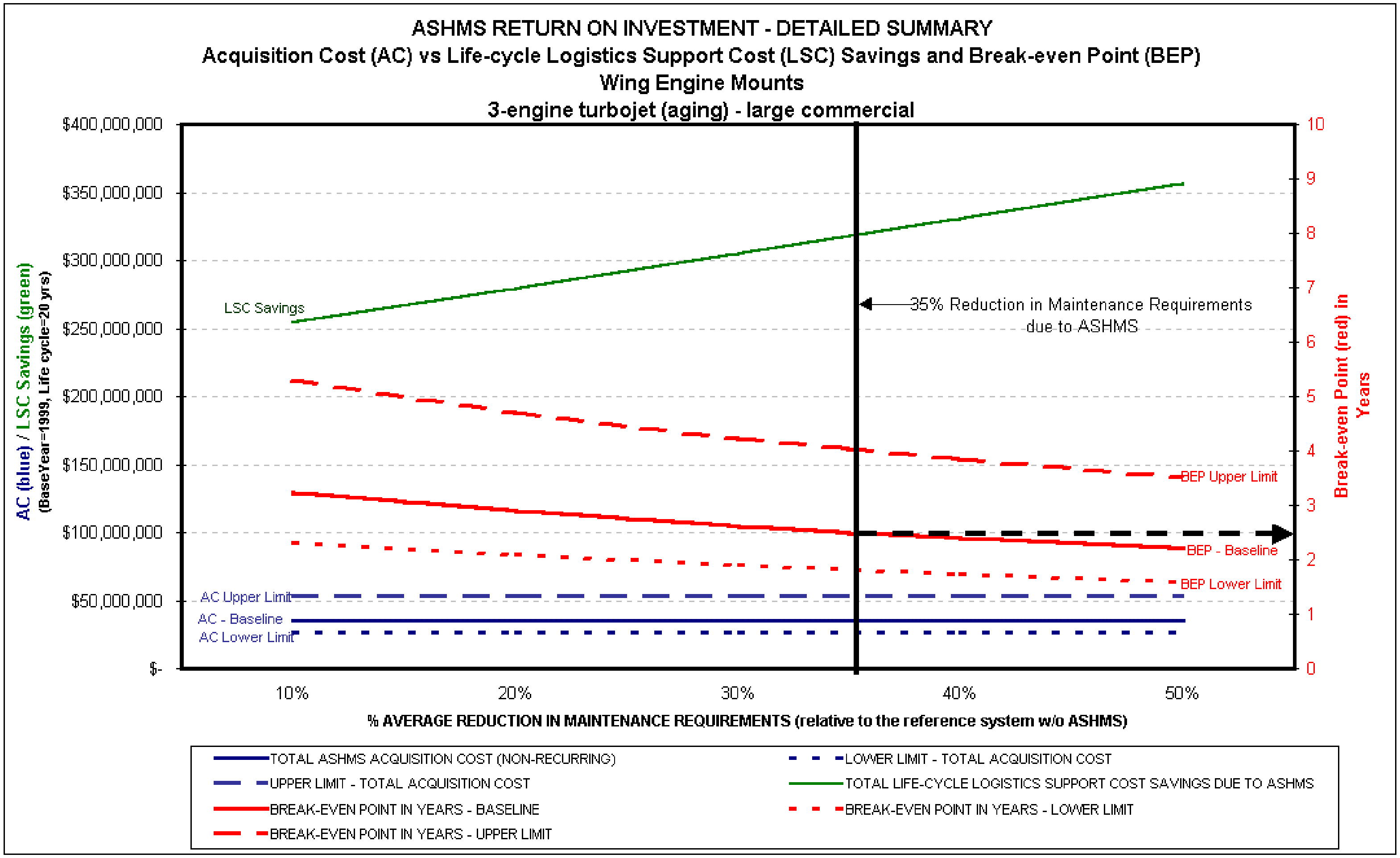


Figure 3-6: Return on Investment Detailed Summary, Wing Engine Mounts, 3-Engine Turbojet (aging)

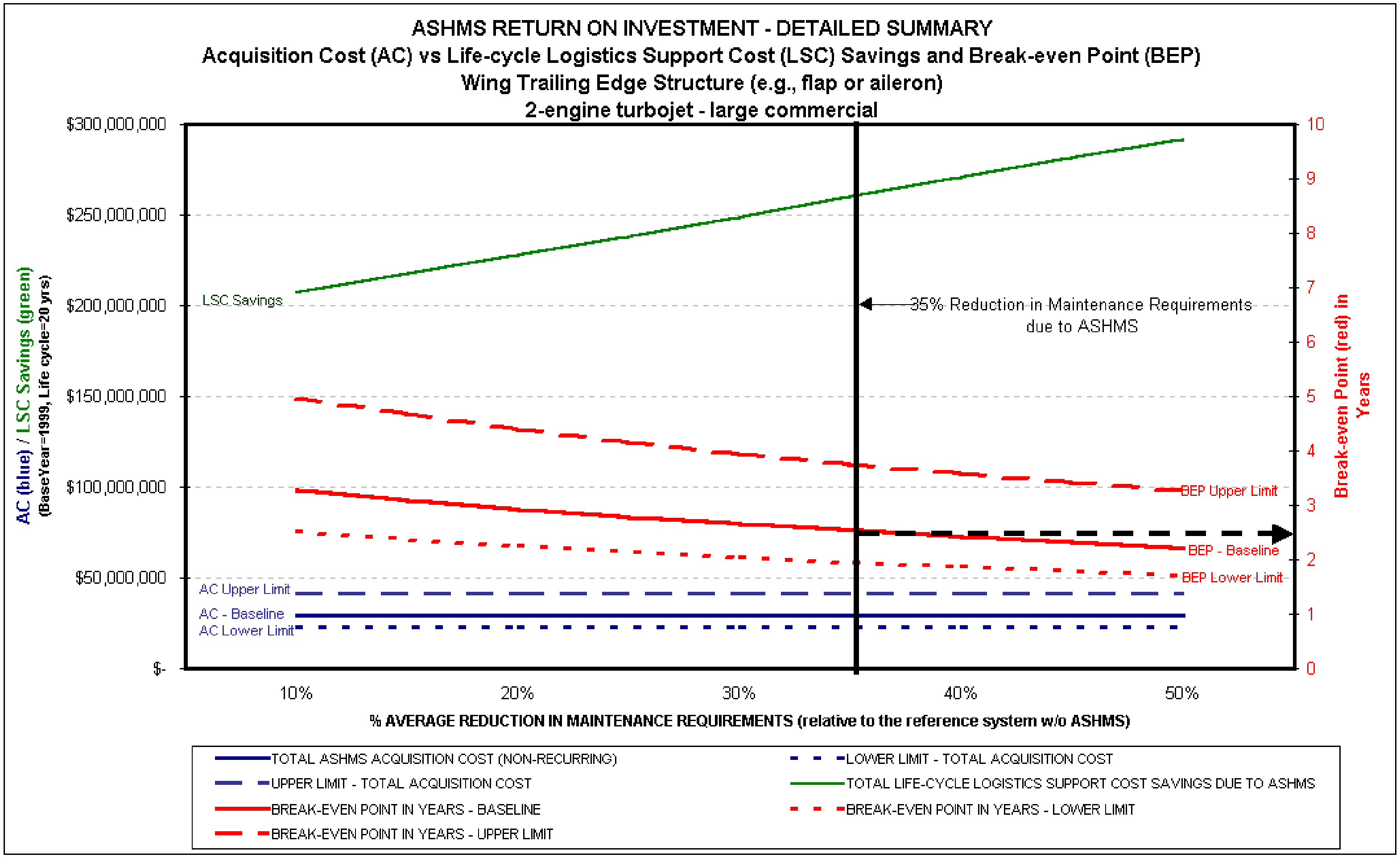


Figure 3-7: Return on Investment Detailed Summary, Wing Trailing Edge Structure, 2-Engine Turbojet

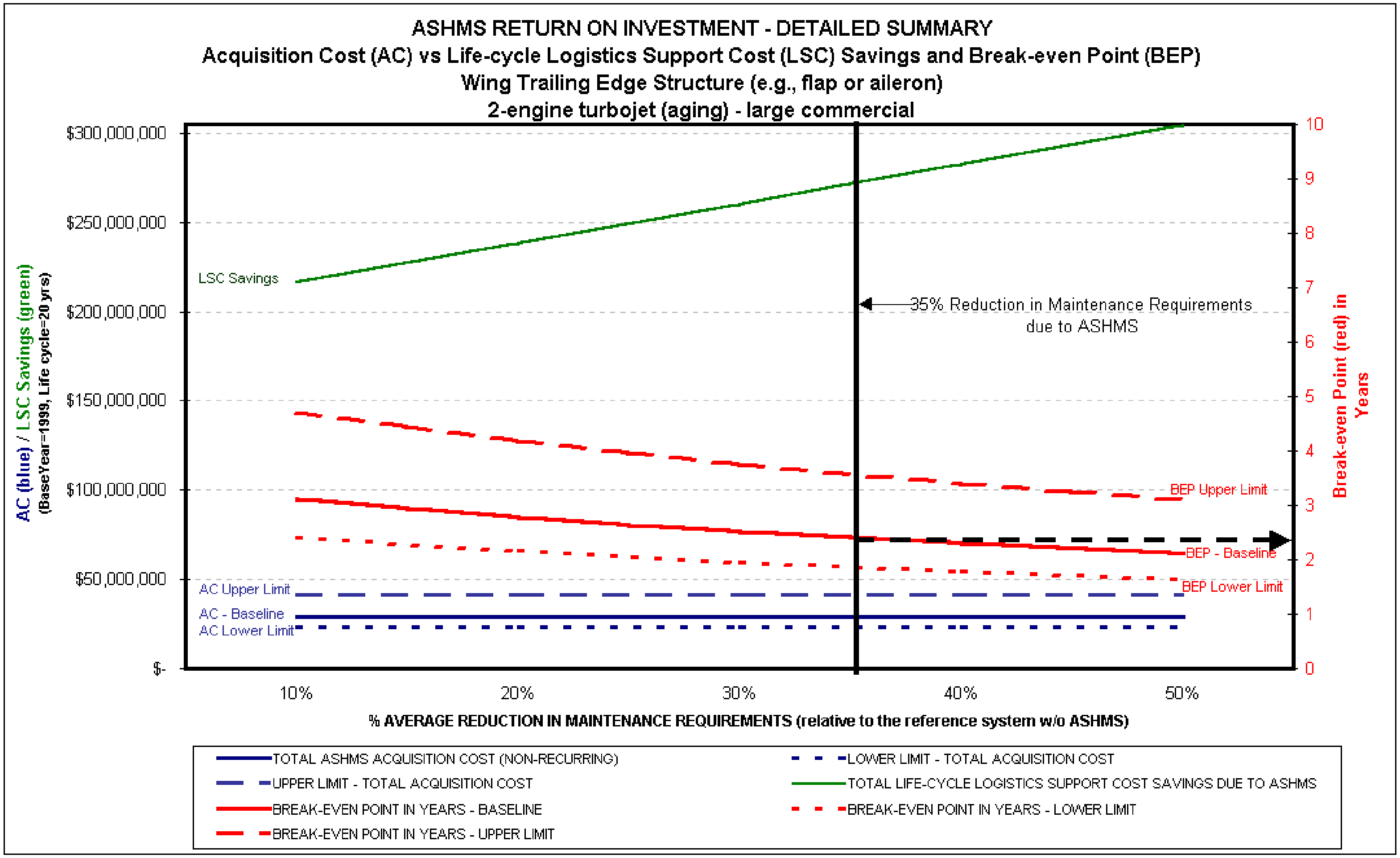


Figure 3-8: Return on Investment Detailed Summary, Wing Trailing Edge Structure, 2-Engine Turbojet (aging)

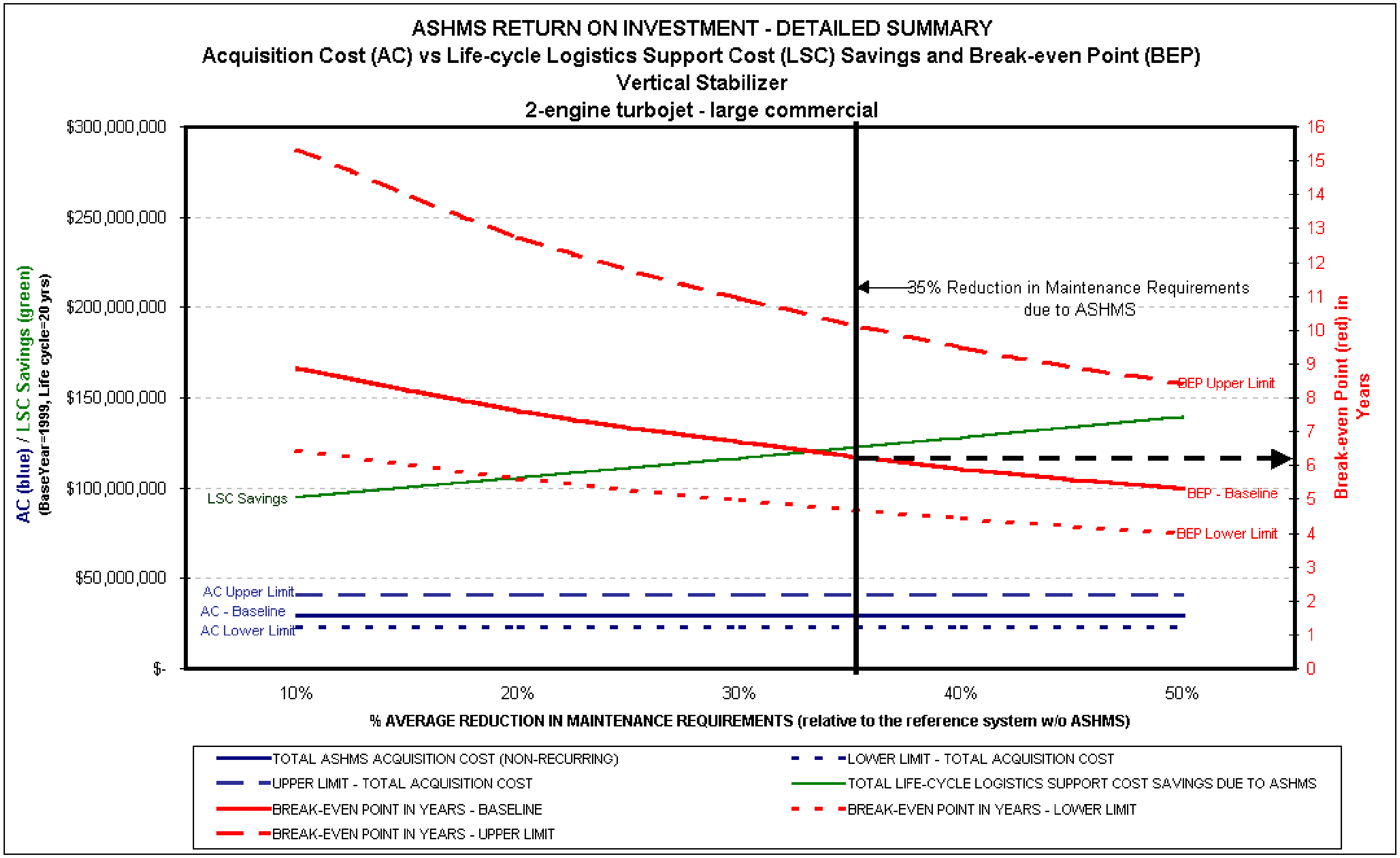


Figure 3-9: Return on Investment Detailed Summary, Vertical Stabilizer, 2-Engine Turbojet

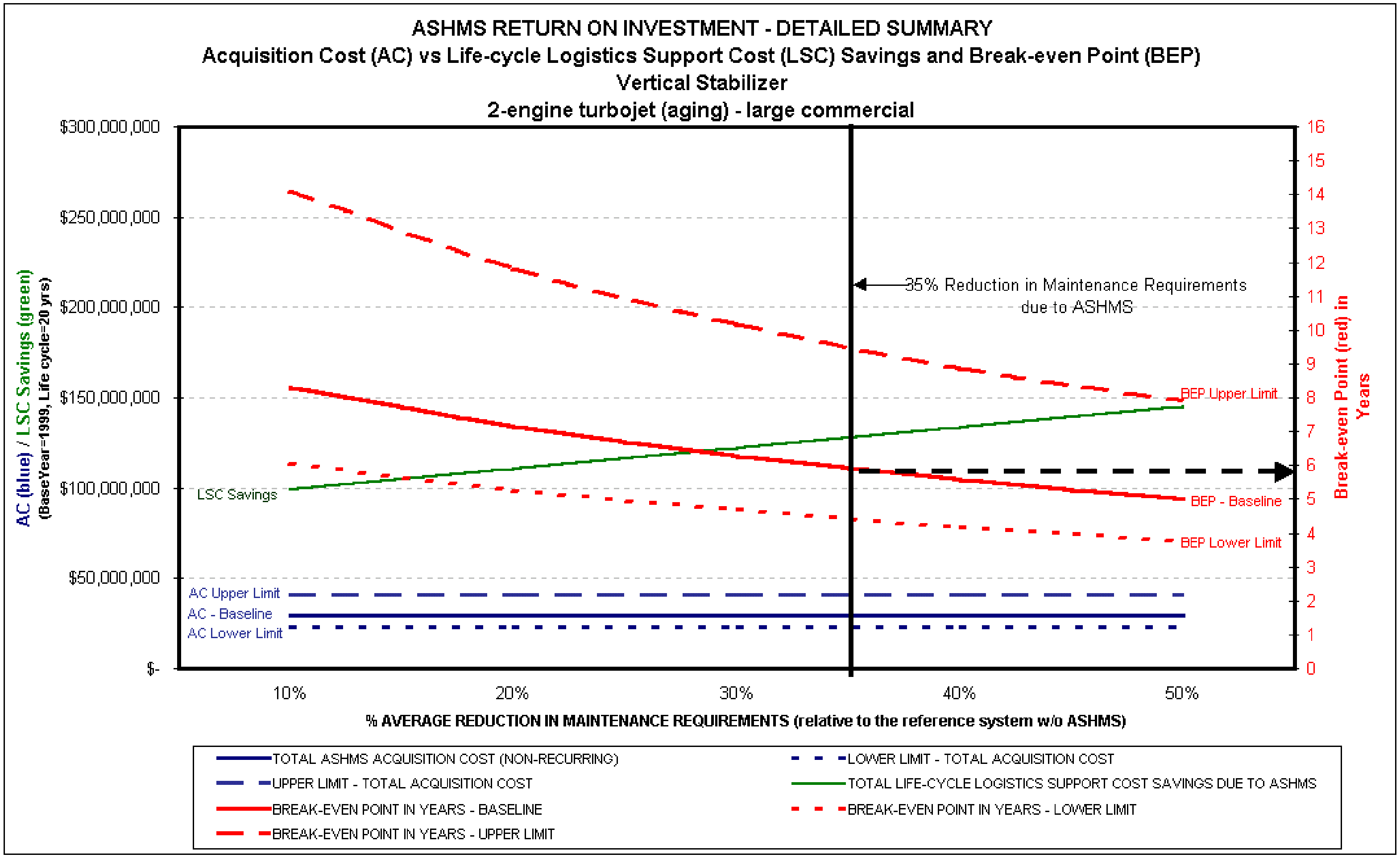


Figure 3-10: Return on Investment Detailed Summary, Vertical Stabilizer, 2-Engine Turbojet (aging)

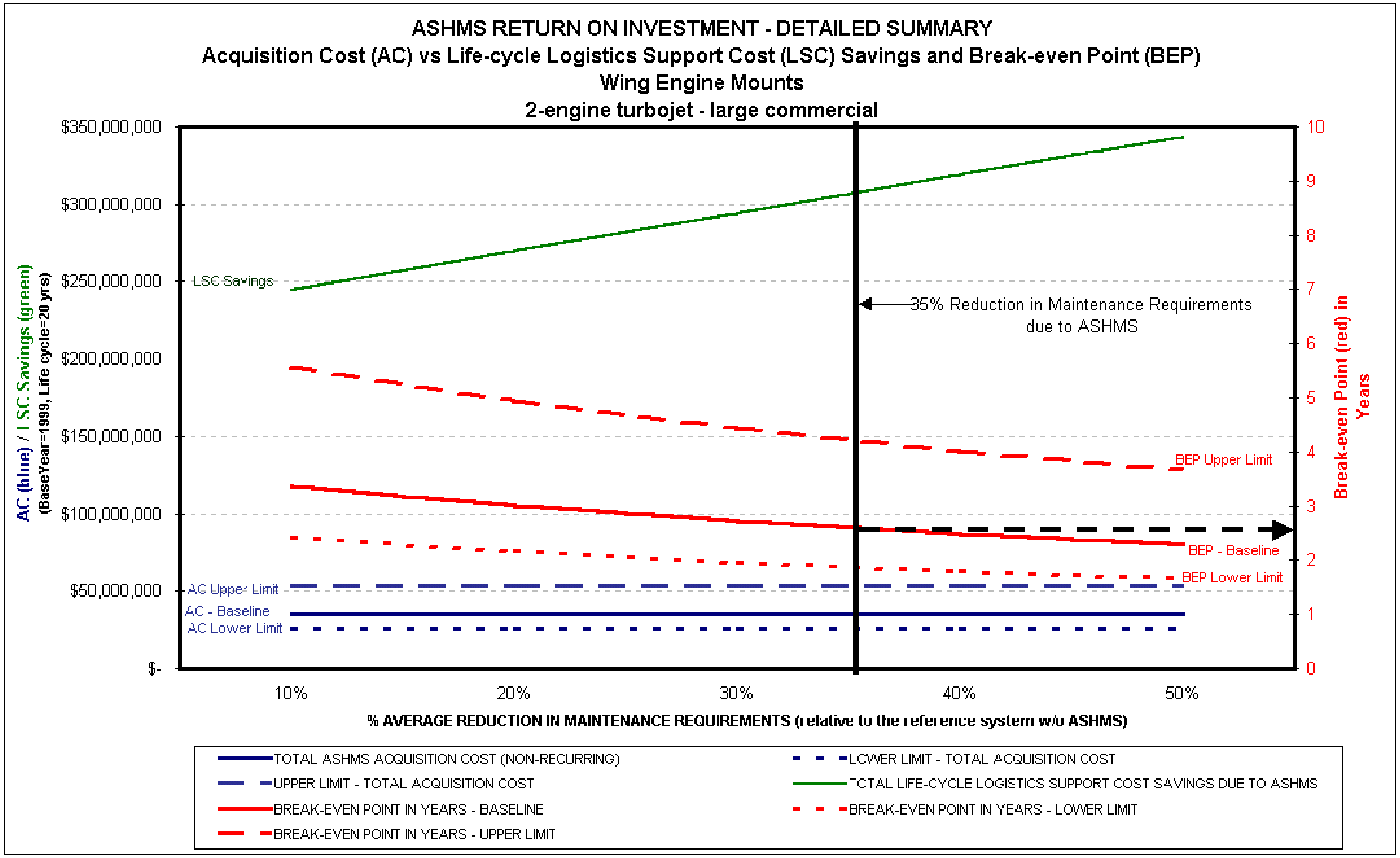


Figure 3-11: Return on Investment Detailed Summary, Wing Engine Mounts, 2-Engine Turbojet

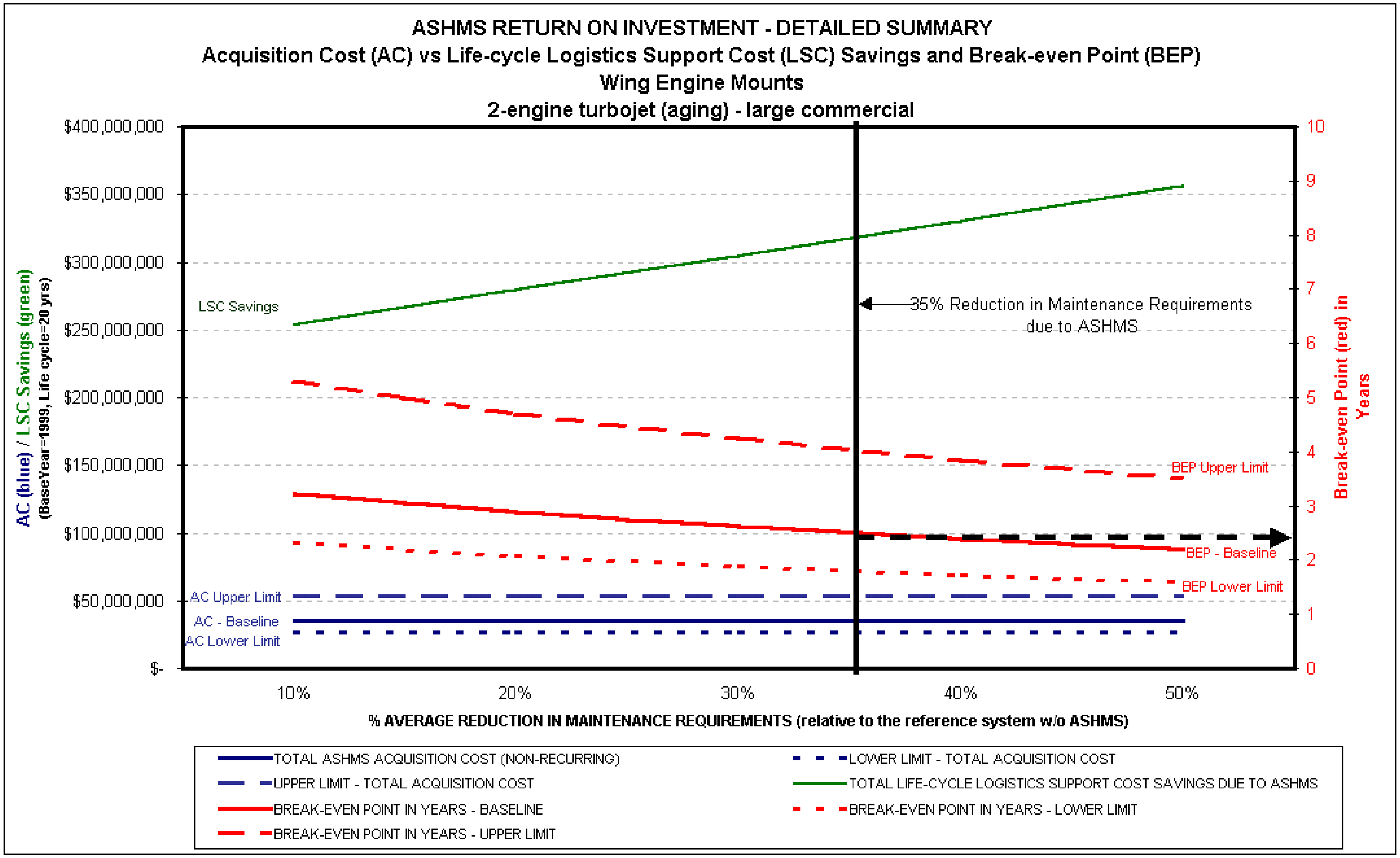


Figure 3-12: Return on Investment Detailed Summary, Wing Engine Mounts, 2-Engine Turbojet (aging)

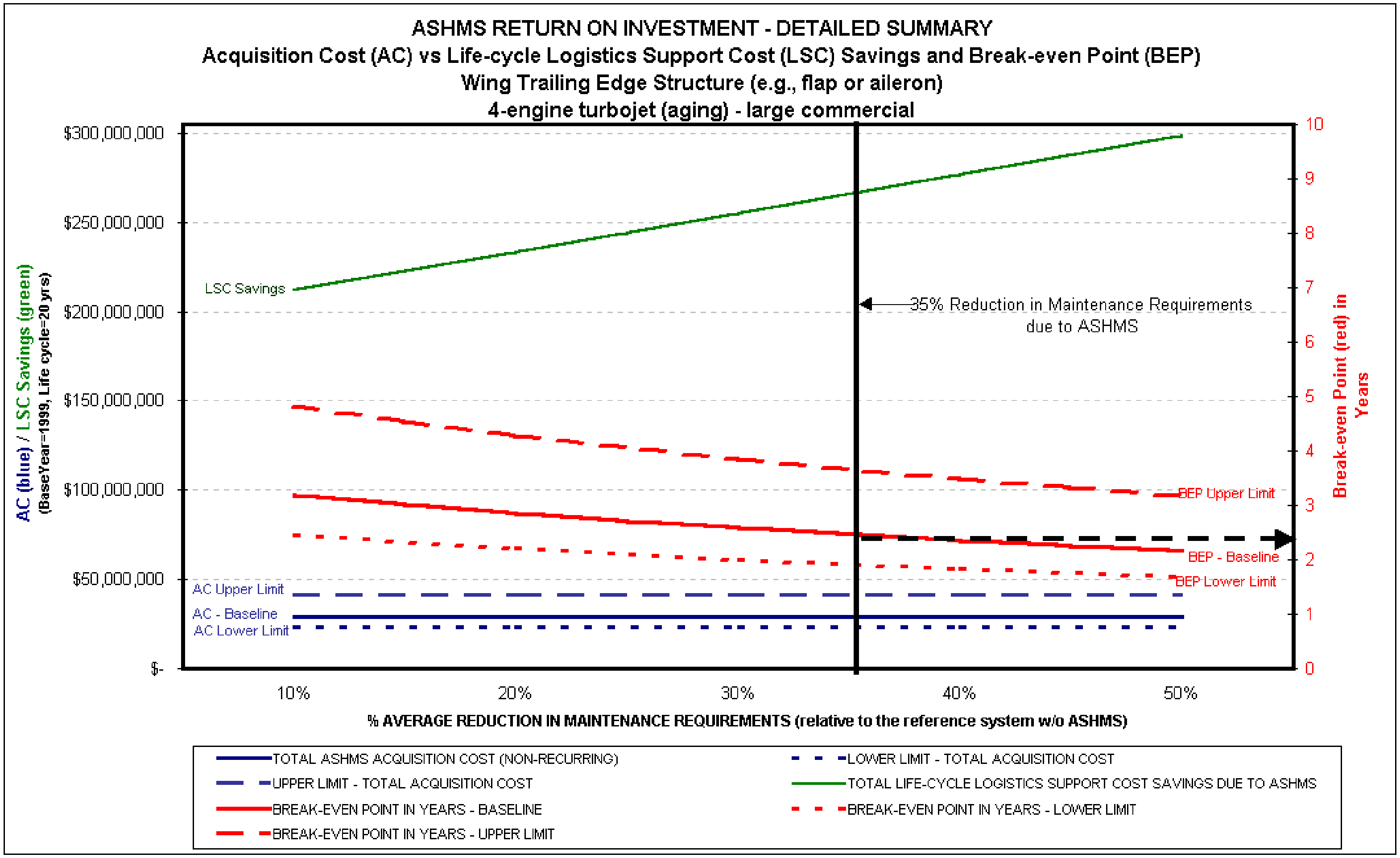


Figure 3-13: Return on Investment Detailed Summary, Wing Trailing Edge Structure, 4-Engine Turbojet (aging)

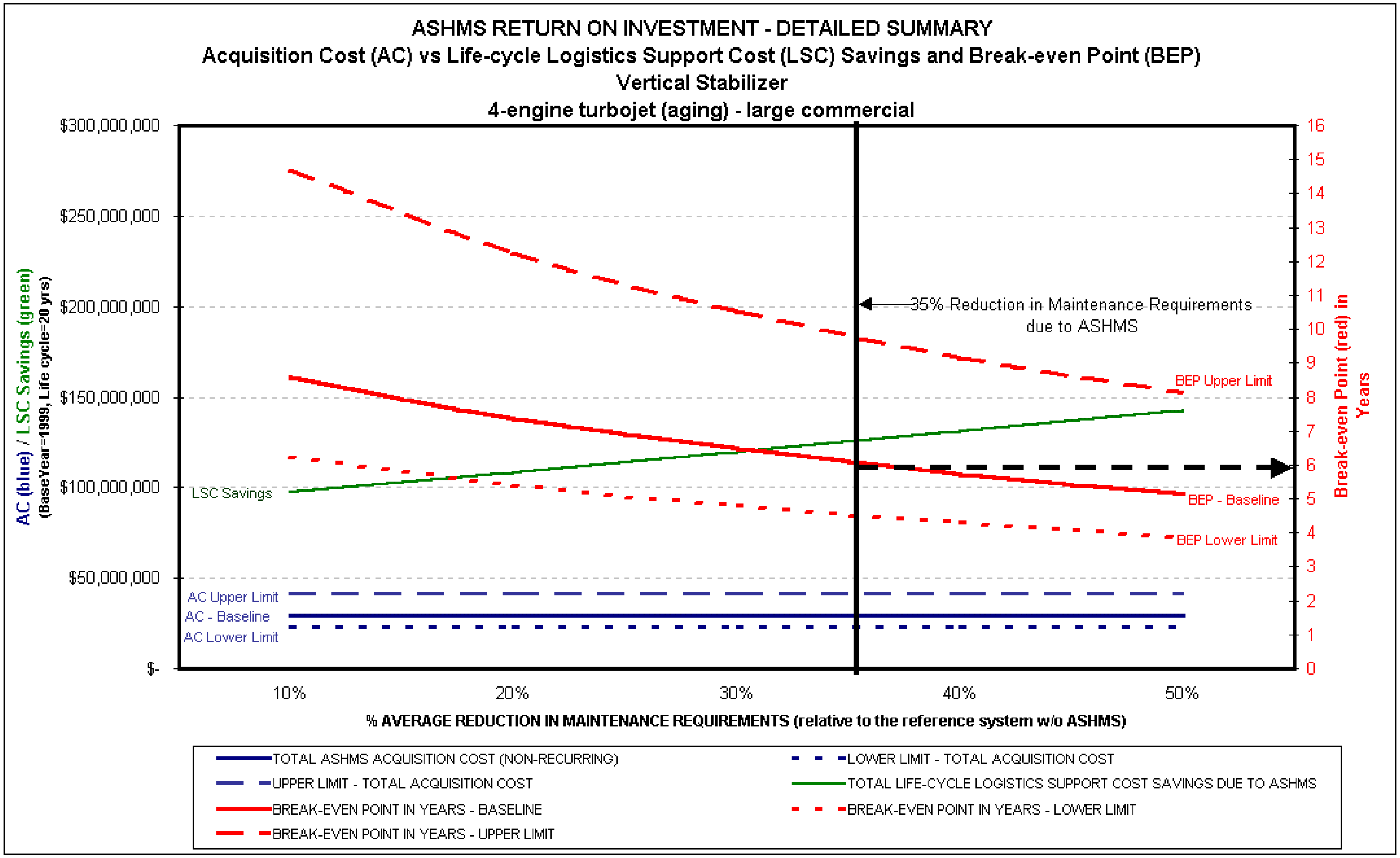


Figure 3-14: Return on Investment Detailed Summary, Vertical Stabilizer, 4-Engine Turbojet (aging)

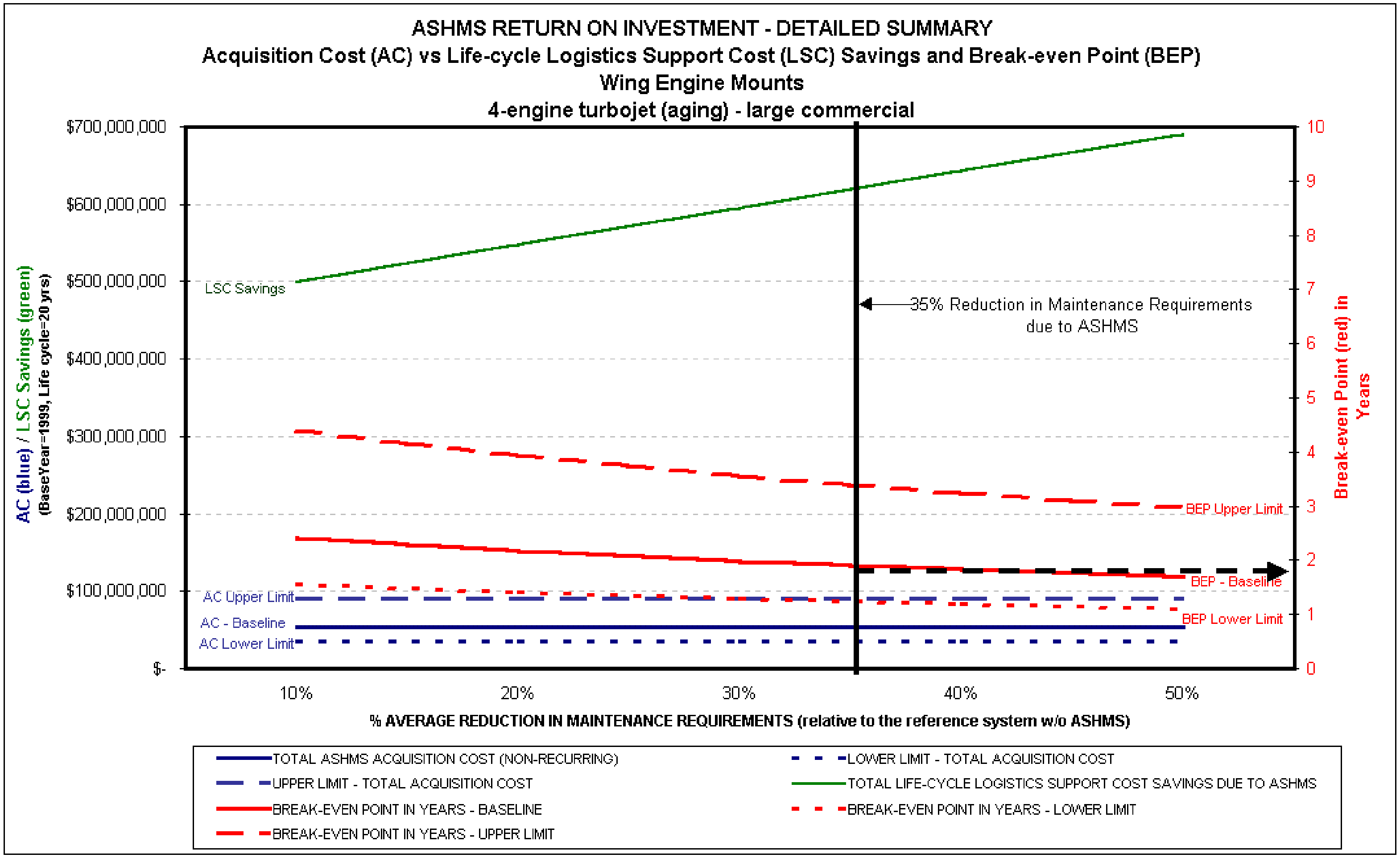


Figure 3-15: Return on Investment Detailed Summary, Wing Engine Mounts, 4-Engine Turbojet (aging)

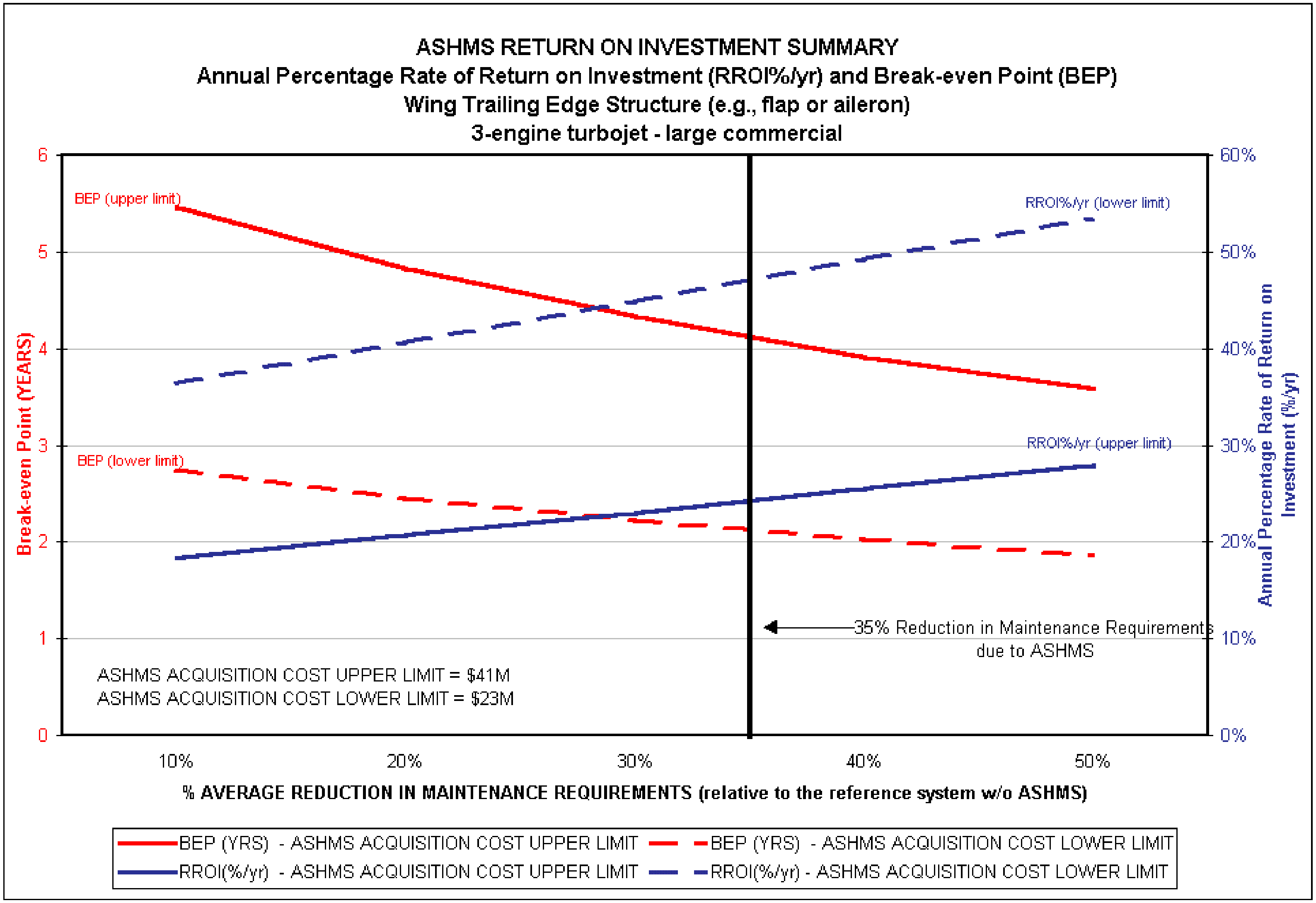


Figure 4-1: Return on Investment Summary, Wing Trailing Edge Structure, 3-Engine Turbojet

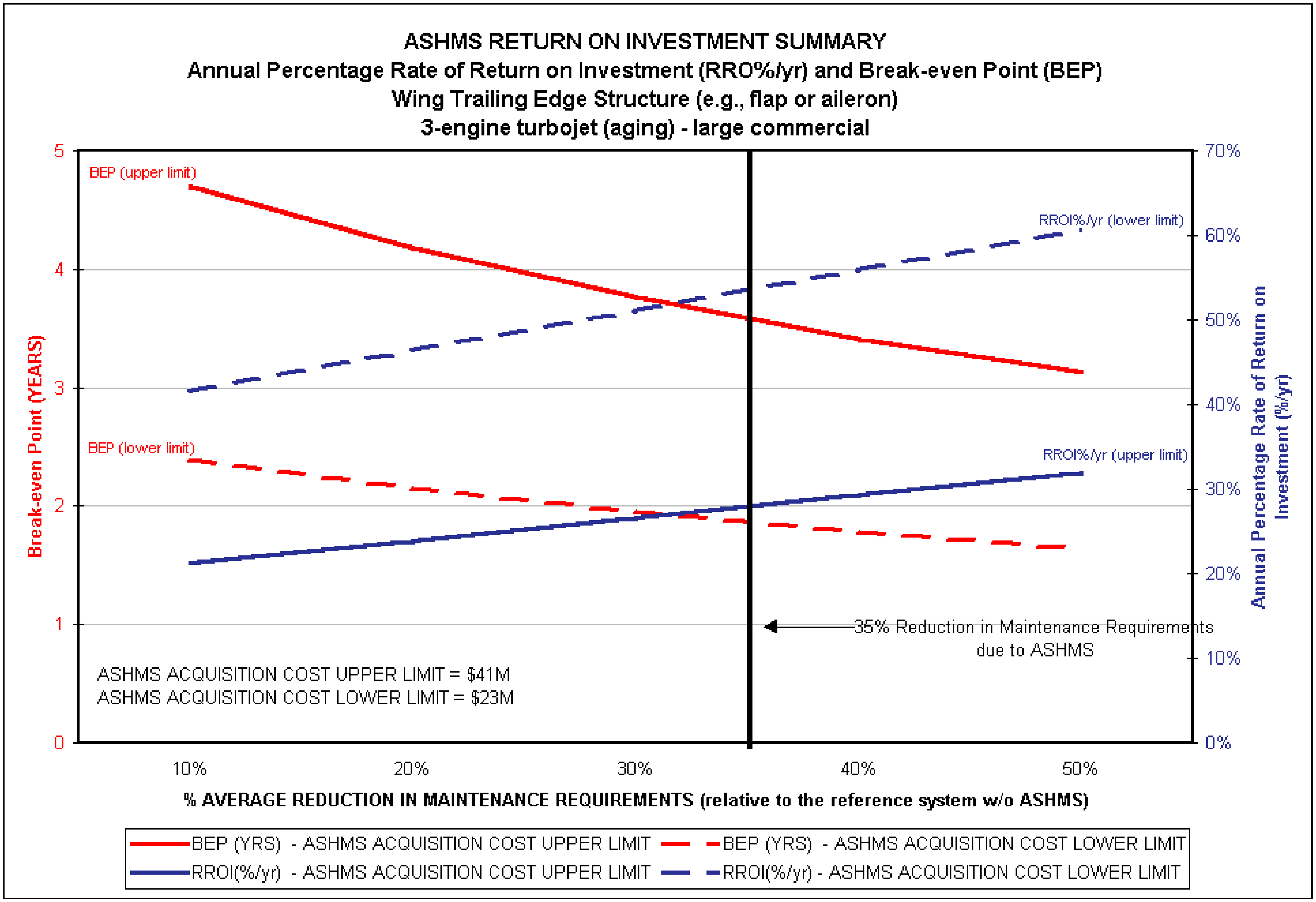


Figure 4-2: Return on Investment Summary, Wing Trailing Edge Structure, 3-Engine Turbojet (aging)

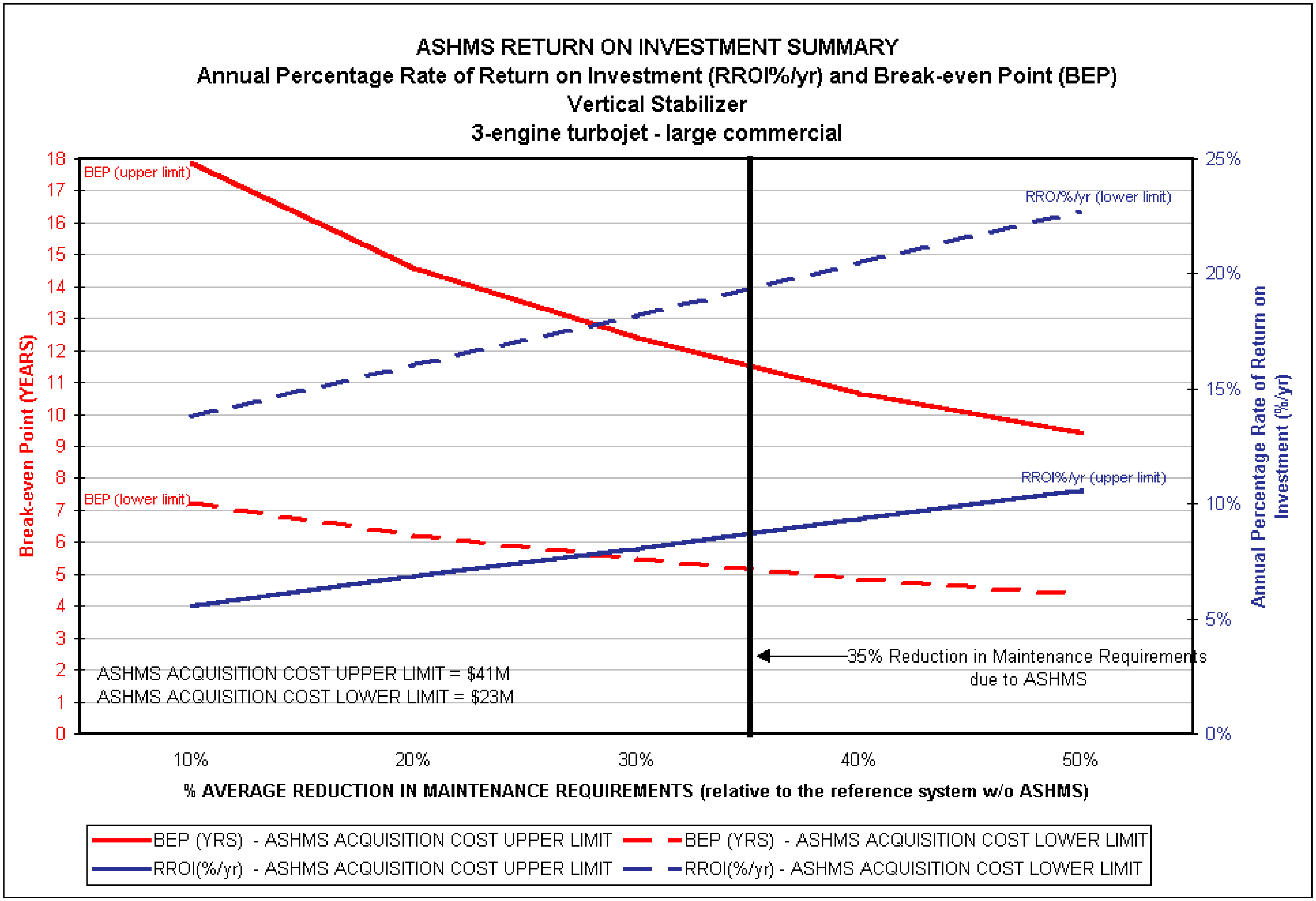


Figure 4-3: Return on Investment Summary, Vertical Stabilizer, 3-Engine Turbojet

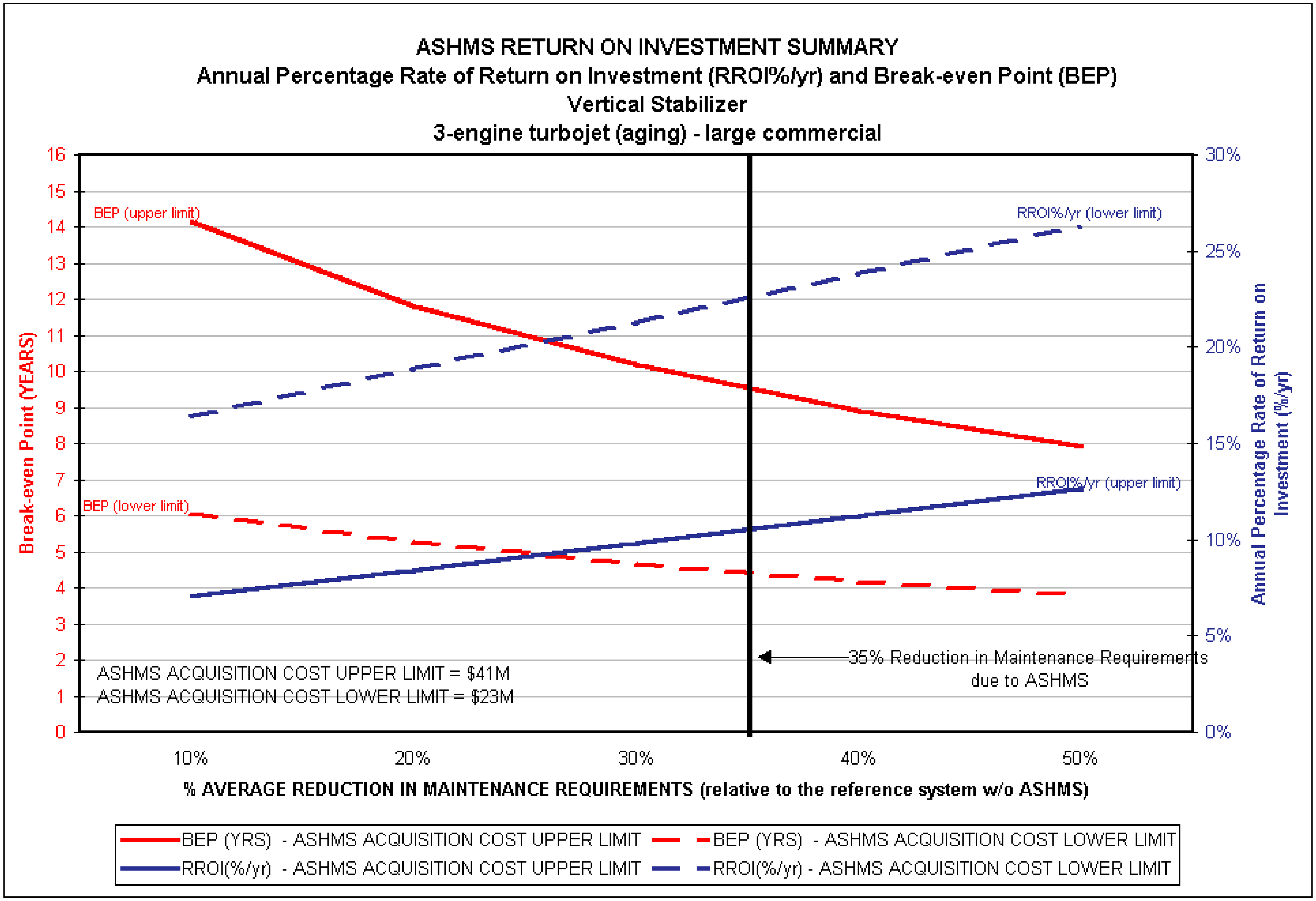


Figure 4-4: Return on Investment Summary, Vertical Stabilizer, 3-Engine Turbojet (aging)

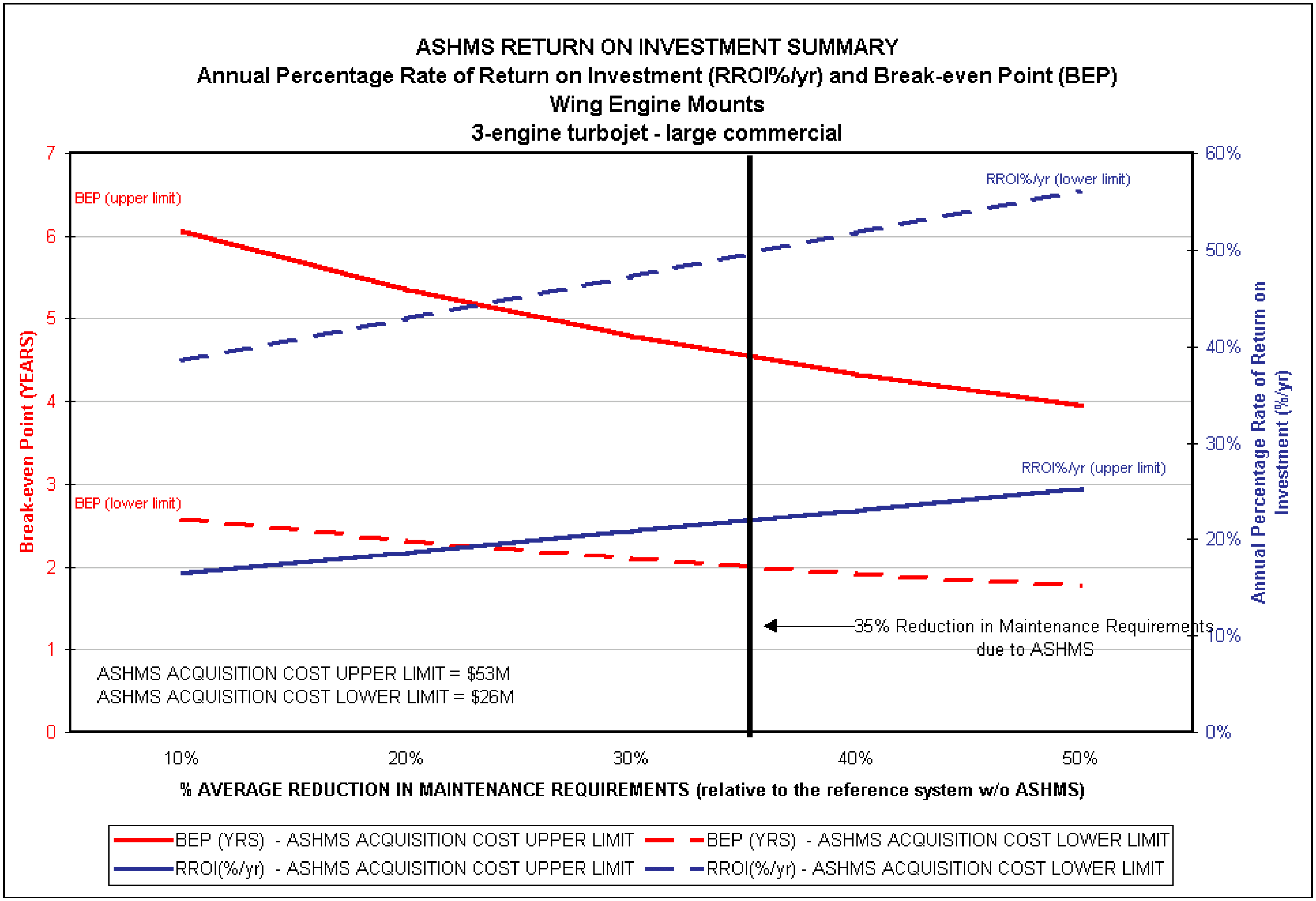


Figure 4-5: Return on Investment Summary, Wing Engine Mounts, 3-Engine Turbojet

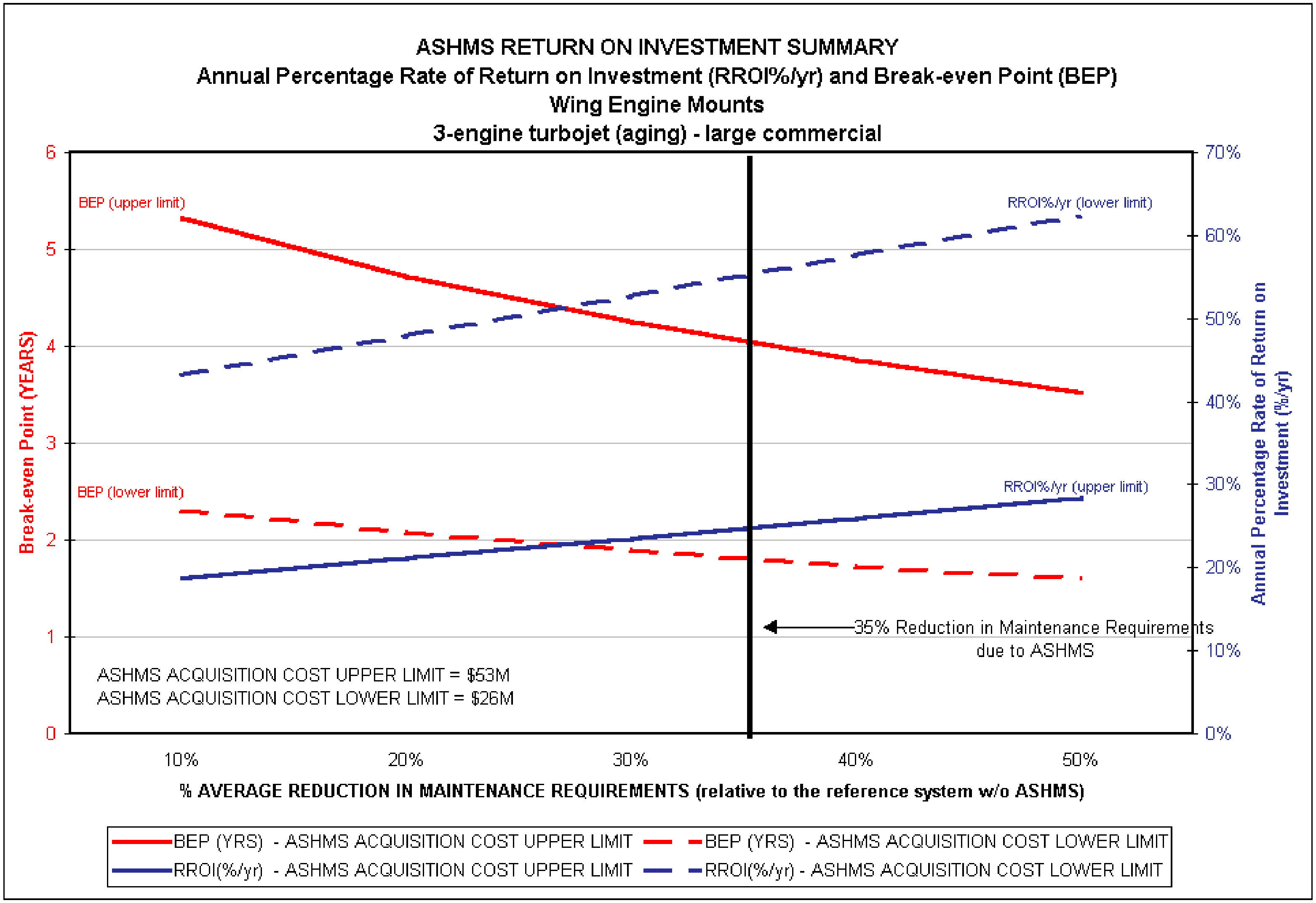


Figure 4-6: Return on Investment Summary, Wing Engine Mounts, 3-Engine Turbojet (aging)

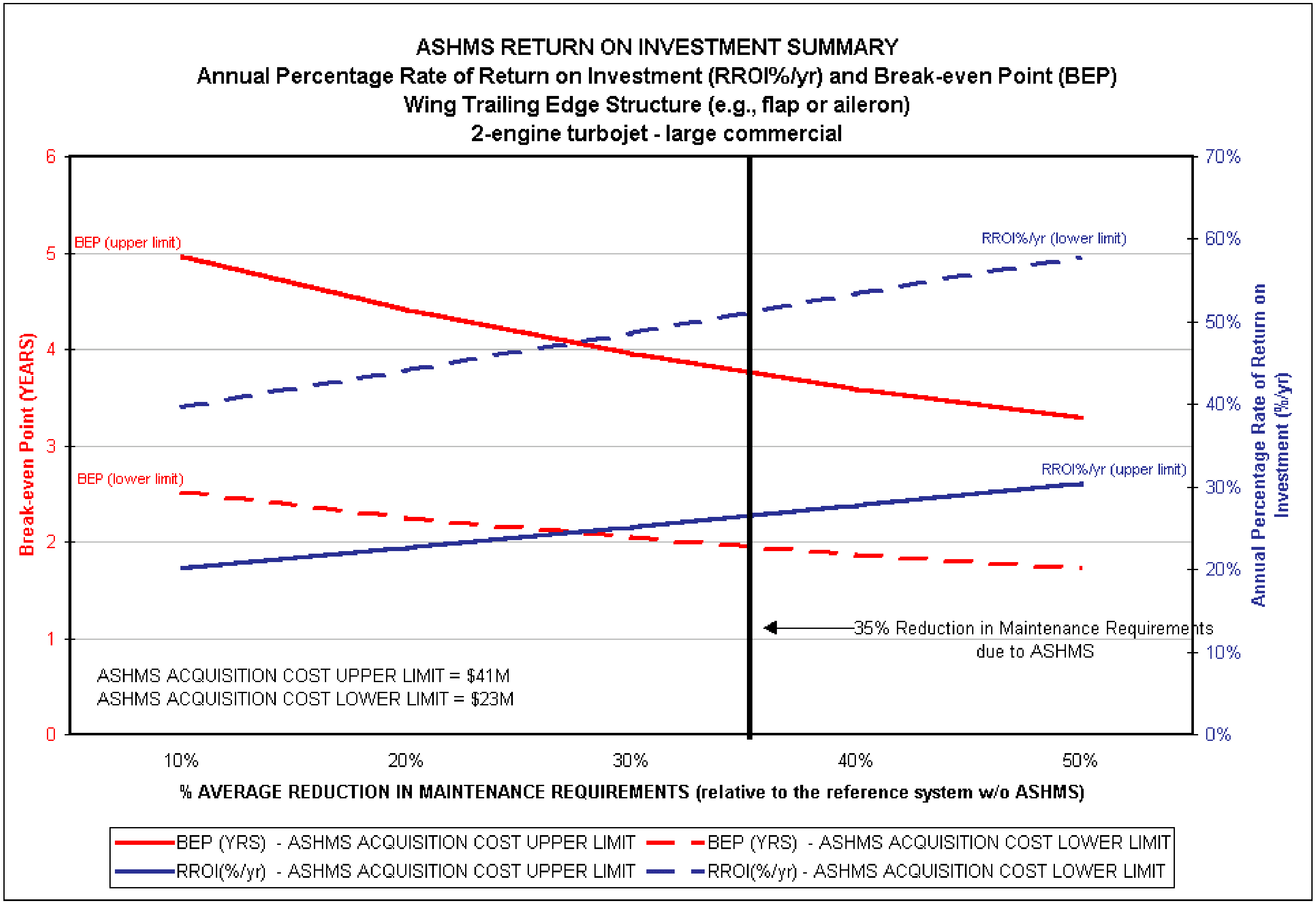


Figure 4-7: Return on Investment Summary, Wing Trailing Edge Structure, 2-Engine Turbojet

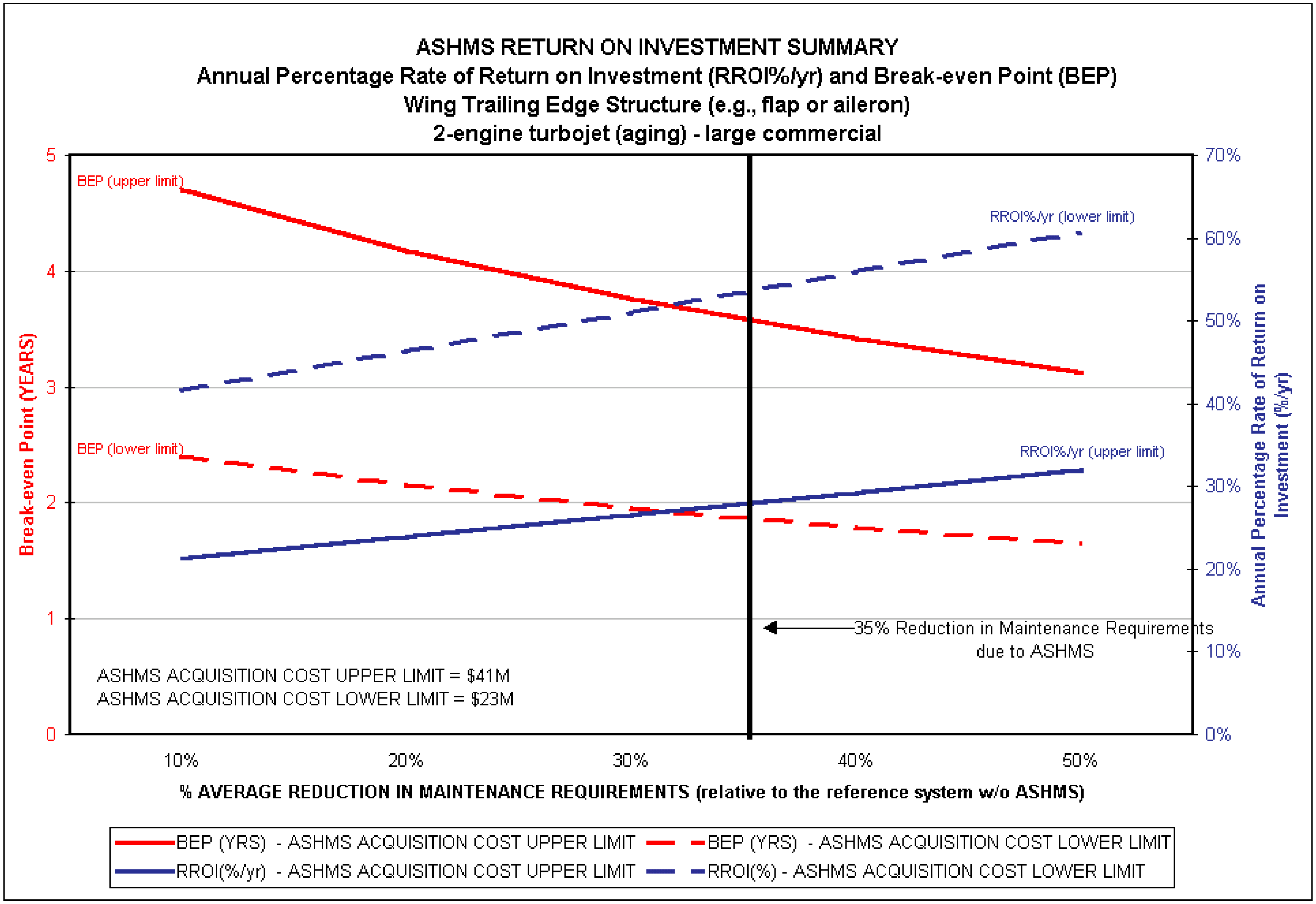


Figure 4-8: Return on Investment Summary, Wing Trailing Edge Structure, 2-Engine Turbojet (aging)

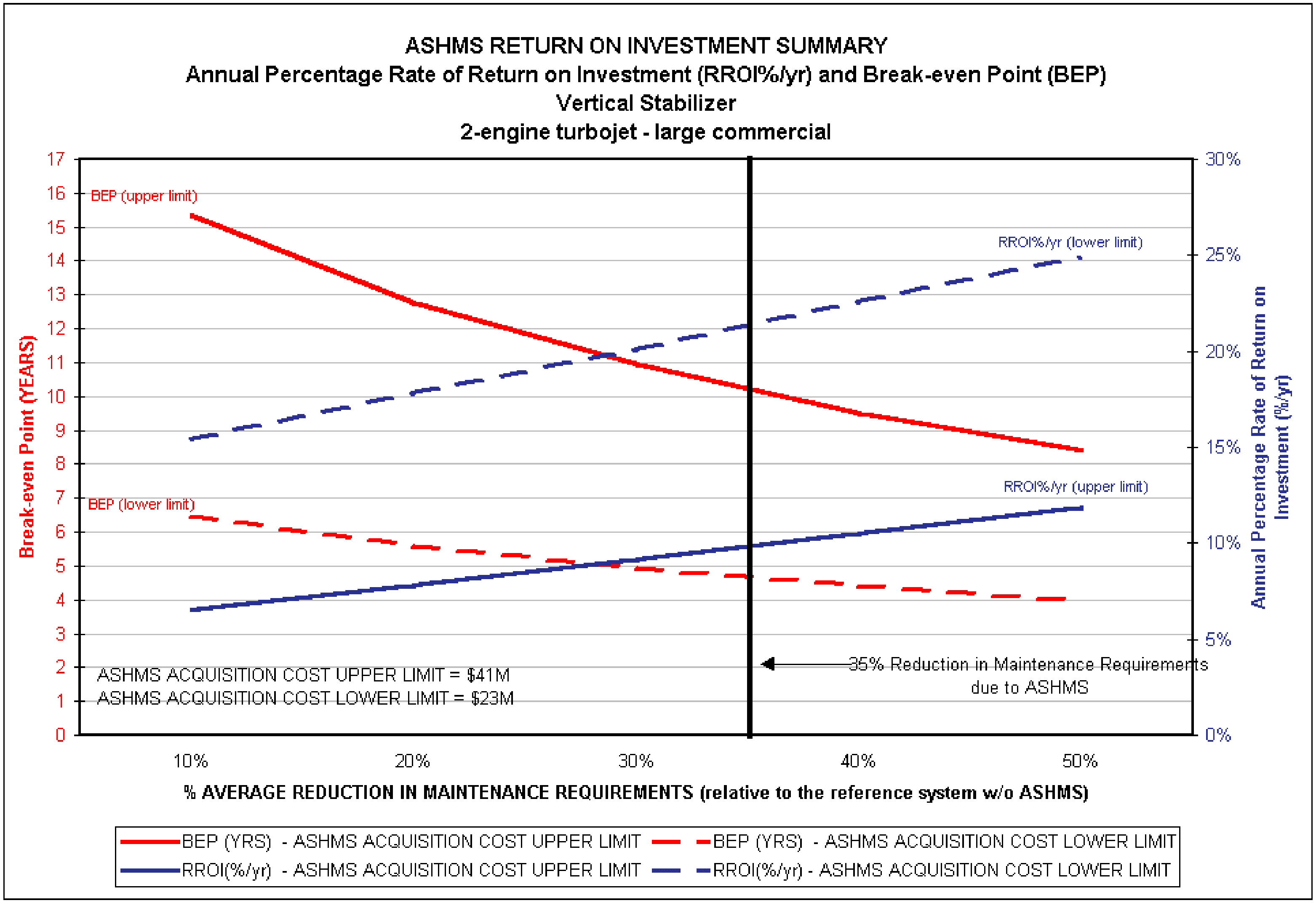


Figure 4-9: Return on Investment Summary, Vertical Stabilizer, 2-Engine Turbojet

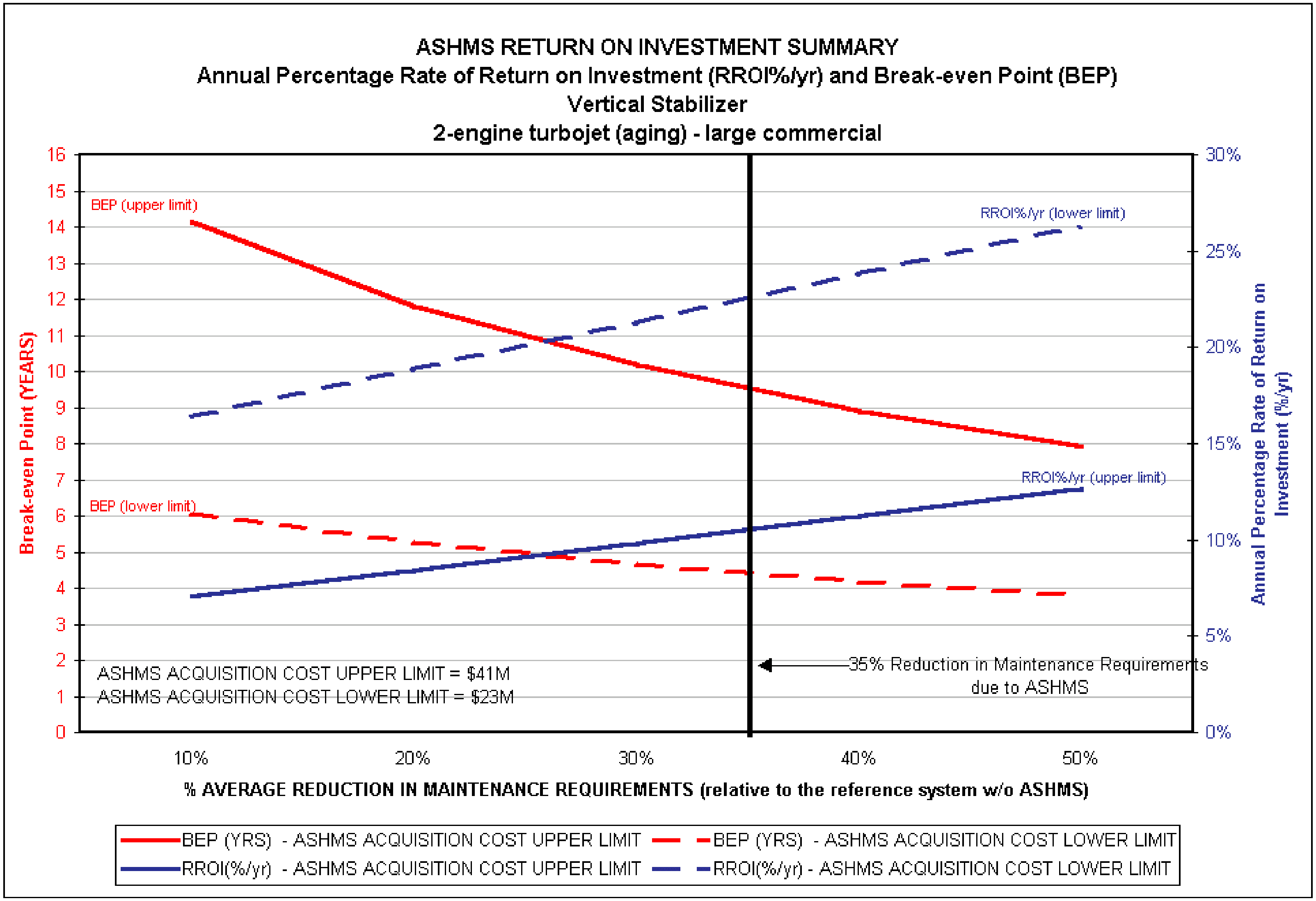


Figure 4-10: Return on Investment Summary, Vertical Stabilizer, 2-Engine Turbojet (aging)

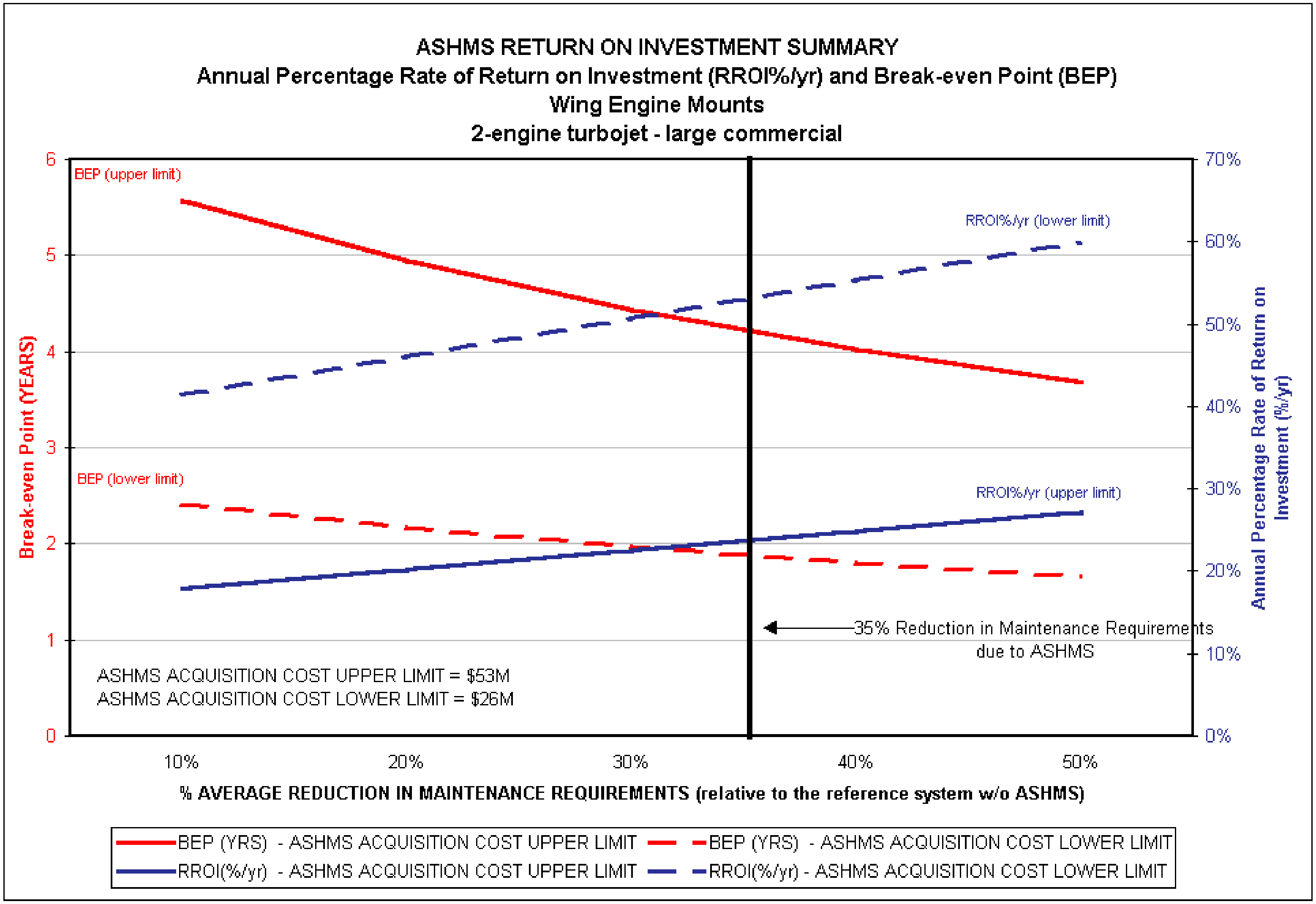


Figure 4-11: Return on Investment Summary, Wing Engine Mounts, 2-Engine Turbojet

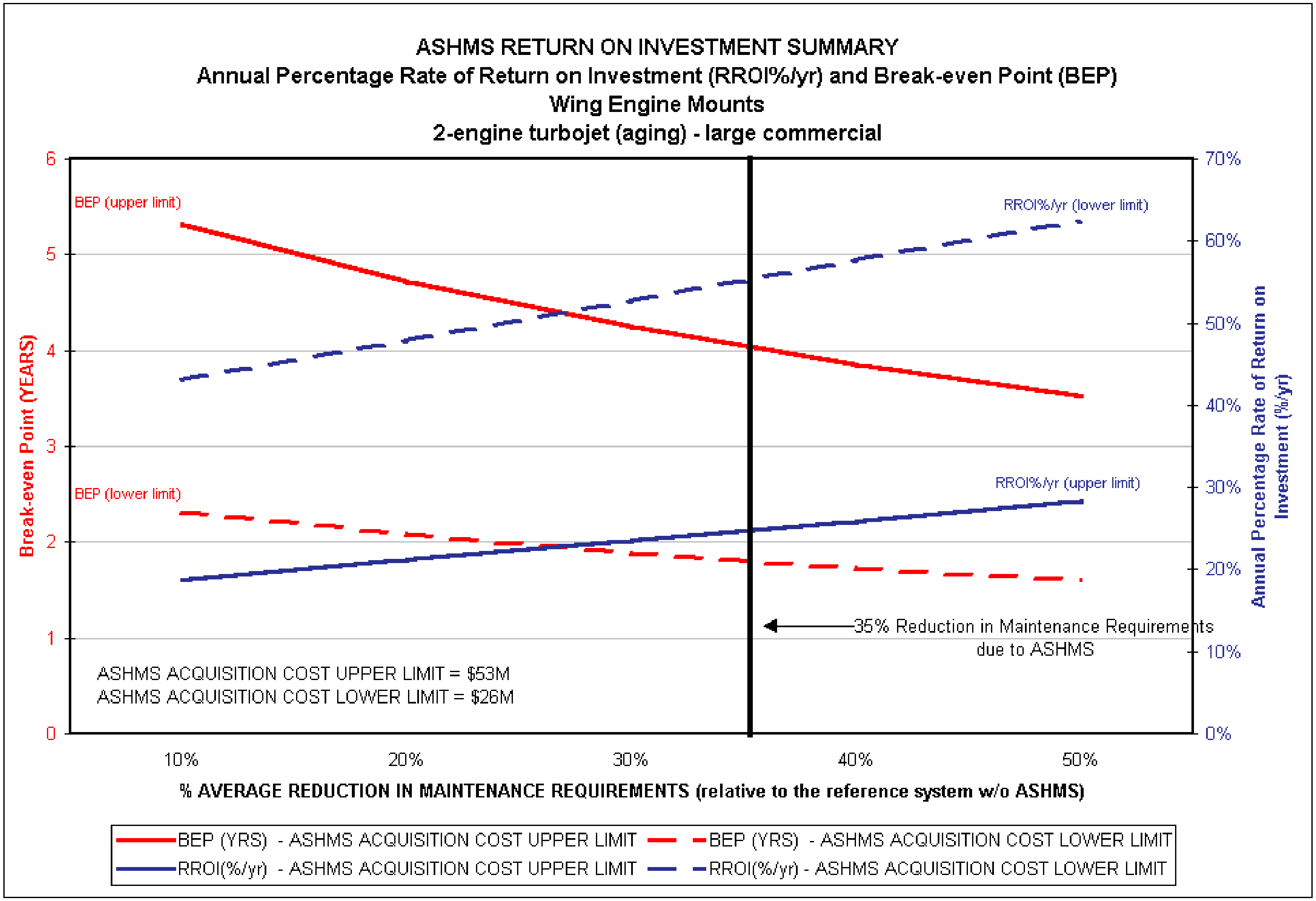


Figure 4-12: Return on Investment Summary, Wing Engine Mounts, 2-Engine Turbojet (aging)

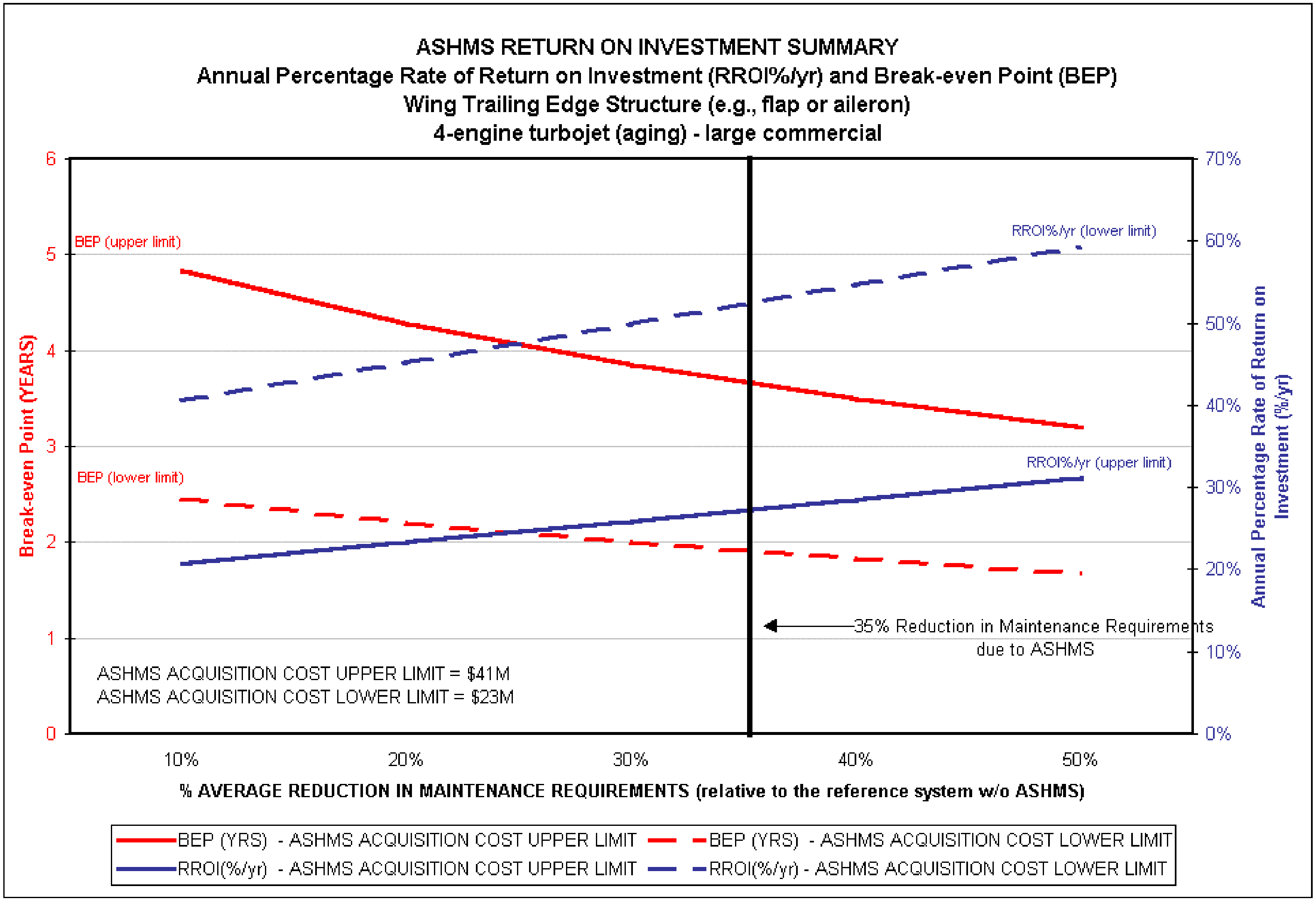


Figure 4-13: Return on Investment Summary, Wing Trailing Edge Structure, 4-Engine Turbojet (aging)

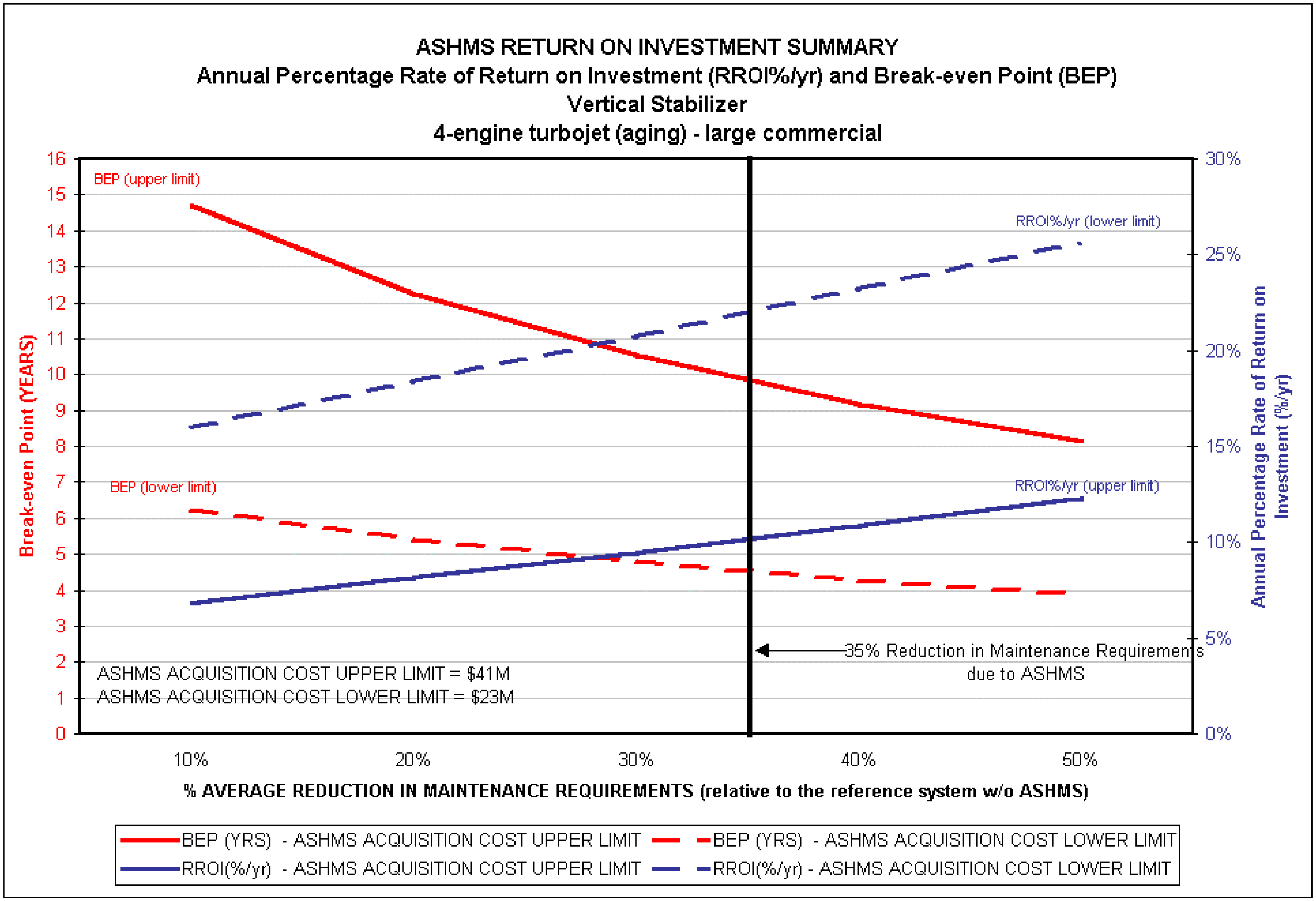


Figure 4-14: Return on Investment Summary, Vertical Stabilizer, 4-Engine Turbojet (aging)

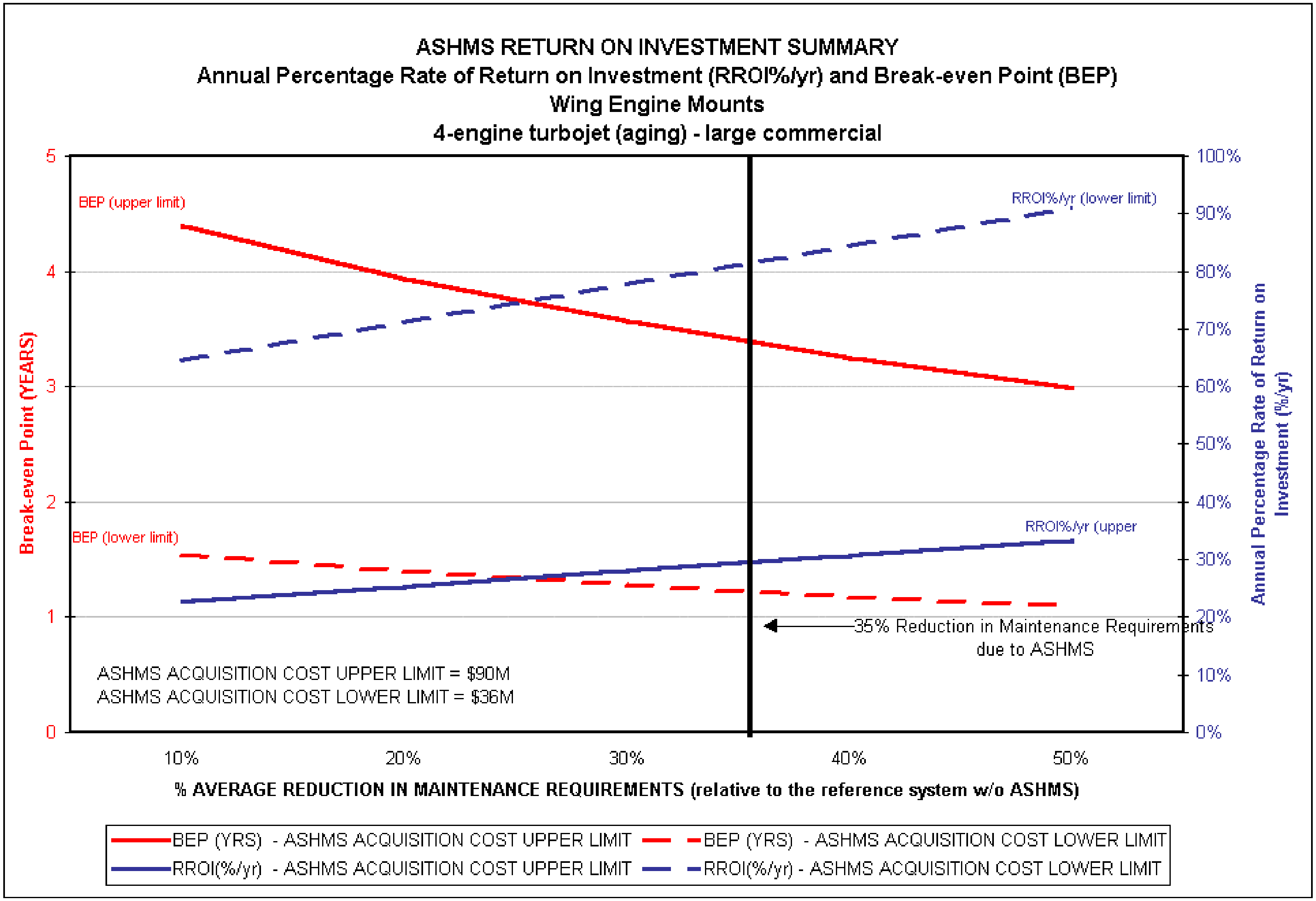


Figure 4-15: Return on Investment Summary, Wing Engine Mounts, 4-Engine Turbojet (aging)

SECTION SEVEN

BENEFITS FROM A NON-ECONOMIC PERSPECTIVE

7.0 INTRODUCTION

This section focuses on the measures of merit relative to logistics streamlining, engineering and technology benefits, safety and performance, impacts on future generation systems, and other operational and logistics considerations related to the effective use of ASHMS technologies. While these factors can and do influence economic feasibility, it is the intent of this section to identify these considerations primarily on a non-economic level.

7.1 ON-CONDITION MAINTENANCE AND LOGISTICS STREAMLINING

Structural health monitoring is an enabling technology that drives the primary and most obvious benefit: the opportunity for enhanced safety through on-condition maintenance and streamlining logistics support for advanced aerospace structures. In these scenarios, the periodicity of maintenance actions, including inspections and repairs, are determined by ASHMS-indicated breaches in structural integrity safety limits. In this way, more comprehensive vehicle health and life cycle management are afforded. This, in turn, enhances the operational availability and reliability of the aircraft and the fleet, and provides a direct opportunity for accident reduction and safety improvement.

If ASHMS technologies are effectively deployed, they can provide in-time (real-time or near real-time) indications of compromised structural integrity prior to life-limiting failure or fatigue. This can lead to earlier diagnosis and repair of affected components that might otherwise fail during flight. Obviously, this has cost savings implications in terms of the reduced extent of repair required, reduced necessity for component replacement (as opposed to repair), and reduced operational downtime. However, it also has the potential for enhancing overall user acceptance of the aircraft relative to its enhanced safety record and reliability. For example, ASHMS may indicate a breach in the integrity of a component (such as a critical wing member) that could cause a degradation in structural performance (such as early onset of wing flutter) to occur. Ignorance of this condition can lead to premature component failure, while early awareness of the condition can facilitate timely correction, control, or mitigation of the defect or flaw. In summary, fewer component and aircraft failures are associated with fewer accidents, reduced loss of systems, and reduced loss of human lives and property.

In the strictest sense, relative to operational and logistical considerations, there are a number of additional perspectives from which these benefits can be analyzed, including:

- Reduced scheduled maintenance requirements. If scheduled (and sometimes unnecessary) maintenance, including inspection and repair activities, can be reduced or eliminated, the required supporting infrastructure (i.e., NDE/I equipment, repair equipment, manpower, and materials) may be reduced.

- Operational Performance. In addition to providing the capability of detecting and assessing life-limiting conditions, ASHMS technologies can enable near real-time feedback of the performance of structures in relation to approved design specifications and operational criteria. For example, an ASHMS database can be used to maintain an engineering description of both the initial system performance and any degradation that may occur in that performance over the life of the component, as related to the structural usage and condition parameters measured by the sensors. Maintenance actions may then be enabled, not only when the system requires repair, but also when the system performance is outside acceptable specifications. Essentially, the ASHMS provides the opportunity for relating measurable control parameters to system performance for improved performance-driven life cycle management of the aircraft and the fleet.

- Environmental Considerations. The harmful effects that aircraft maintenance actions have on the environment have been clearly demonstrated. Each time an aircraft undergoes a maintenance action, chemical agents required for the performance of the maintenance produce potentially harmful effects on the environment. For example, the chemicals required for stripping paint from the aircraft can contribute to air and water pollution and may have deleterious health, even carcinogenic, side effects on humans exposed to the agents. In addition, waste products generated by the use of these agents must be treated for proper use and disposal. While there are efforts currently underway to replace such chemicals with less hazardous agents and to refine maintenance practices to minimize human exposure and establish acceptable disposal processes, the best way to mitigate the risks associated with the use of these agent is to minimize or eliminate their use. Consequently, reducing the number of maintenance actions translates into significant reductions in the use of environmentally harmful agents. In this way, on-condition maintenance approaches that capitalize on the use ASHMS technologies offer the potential for significantly enhancing environmental friendliness.

- Resource Availability. A comparative example may aid in illustrating these considerations.

  - In a scheduled maintenance scenario, each aircraft is pulled from service after a specified number of operational flying hours or calendar days/months. The aircraft then remains out of service while it undergoes destructive and nondestructive inspections, which currently may include variations on ultrasonics, x-ray, optical, and audio interrogation techniques. In these cases, even the most "non-intrusive" inspections generally require some level of paint stripping, component removal, part removal or disassembly, component fixturing for scanning, scan plan generation, scan plan execution, and subsequent data analysis. (NDE/I technologies often do not provide real-time results.) A rigorous analysis might include a 100% inspection of all structural components. This process is required just to detect the presence or absence of damage or degradation to the component. The size of the fleet drives the flux of the aircraft as they go through the scheduled procedure: the larger the fleet, the more aircraft that are down for periodic maintenance at any one time, and the more supporting infrastructure (equipment, facilities, personnel, and material) that is required. Once an indication of damage or degradation is found, a maintenance technician makes a manual determination of the extent of the damage and its anticipated impact on the structural integrity or functional performance of the component. If repair is required (in some cases the extent of damage may not be sufficient to warrant repair), the structure is further torn down for inspection and repair or replacement, as required.

– In an on-condition maintenance scenario, the above process occurs only when a maintenance condition is indicated and validated by the ASHMS. Therefore, the aircraft is only removed from service when the requirement for maintenance is specifically justified. It is anticipated that the sensor system will determine the presence of incipient damage and degradation so that the time that the aircraft remains out of service will be significantly less than described above. In addition, the need for supporting infrastructure is reduced since not every aircraft must undergo rigorous inspection procedures every time it is brought in for maintenance.

7.2 ENGINEERING BENEFITS

There are also engineering benefits associated with the capabilities of next generation ASHMS technologies. For example, the development of an historical maintenance record for aircraft structural components (using data generated by ASHMS), as a function of operational utilization, structural integrity, internal condition, and performance, can give valuable insight into:

- <u>Validation of the design and engineering test models</u>. The historical record of component structural health will provide critical data that may be fed back to design, engineering, and test organizations for analysis, verification, and validation. These empirical data provide unique insight into the dynamics and functional evolution of these structures that, in turn, can be used in association with the design models for evaluation, update, and enhancement of system performance specifications and limits criteria.

- <u>Actual response of the component under operational conditions</u>. It has been shown that, even in rigorous component level laboratory testing, it is often difficult, if not impossible, to duplicate the conditions that a structural component experiences during operation. The result is that laboratory testing is often not sufficient to determine the structural state of a component and the impact that operational conditions (e.g., environmental extremes and thermomechanical loading) have on the integrity and performance of the component. Consequently, ASHMS historical data are critical to understanding and controlling the fundamental mechanical behavior, performance, and condition of a component under actual operating conditions.

- Improvement in the design of future models. ASHMS data, especially as related to flight conditions and performance, can be fed back to on-going design activities for improving the engineering models for next-generation systems. For example, functional relationships between actual performance data and desired performance parameters can provide critical insight into isolating specificities for design improvements in future systems.

- Forensic analysis of structural anomalies. Even with the use of an ASHMS , some structural failures and malfunctions may still occur. An ASHMS can be designed to be robust enough so as to reduce the occurrence of these failures; but, when failures do occur, it is critical to have a historical record of the structural usage, condition, and operational parameters which led to the failure. Careful analysis of these data can lead to a comprehensive understanding of the fundamental mechanisms of failure for control and remediation in the future. In this context, the ASHMS system would provide engineering data analogous to the flight and voice data recorder information currently used in the forensic investigation of field failures.

- Technology extension for in-process analysis of structural anomalies. Manufactured structural components often suffer from microstructural anomalies due to variability in the (1) raw materials used for manufacture, and (2) processes and equipment used in raw materials preparation and end-product fabrication, finishing, and shaping. Consequently, an additional benefit of an ASHMS system is the opportunity for extension of the sensor technology basis for application within the manufacturing process. If new structural components are manufactured with sensors in place for eventual health monitoring, the sensors could also be used to optimize and streamline the manufacturing process to achieve:

  - Improved design performance

  - On-line interrogation and resolution of those material variations and microstructural anomalies which may contribute to downstream structural performance degradation

  - Decreased process design times

– Improved productivity and yield

– Reduced process cycles times

Preliminary research has indicated that such augmentation to the manufacturing process can significantly reduce life-cycle cost and simultaneously enhance the operational capability (e.g., performance, reliability, durability, and supportability) of the end product. In fact, the technological feasibility exists for multifunctional sensors that act as discriminators for process optimization during manufacturing and, later, as sensors for structural health monitoring and condition interrogation during operation.

7.3 TECHNOLOGY INSERTION CONSIDERATIONS

There are a number of technology insertion considerations that must be adequately addressed in order to effectively develop, deploy, and implement any sensor-based system for ASHMS. Furthermore, it should be noted that the feasibility and viability of ASHMS, relative to the benefits described above, are functionally dependent upon the user's operational utilization and support concepts, life-cycle structural integrity management policies and criteria, support resource allocation practices, and data management philosophy.

Certain ASHMS design and operational factors (e.g., sensor selectivity and sensitivity, calibration drift, and reliability and durability under various cyclic stress and environmental conditions) may influence the accuracy, precision, and repeatability of the ASHMS. While a fundamental understanding and control of these factors is critical for the successful implementation and utilization of an ASHMS, it is likely that several strategies may be used, individually or collectively, to mitigate the adverse influences that each of these factors may have on the fidelity and integrity of the ASHMS data. These strategies for sensor utilization and operation are described in the following sections.

7.3.1 Calibration

Data accuracy, precision, and integrity must be appropriately addressed to achieve desired system operational capability. Coherent and repeatable calibration procedures for the ASHMS can be incorporated to ensure the integrity and continuity of the sensor data over time. This, in turn, facilitates a more representative description and characterization of the health and condition of primary structural elements relative to actual operational conditions.

Calibration can be considered a multivariate process that allows independent elements of the system to be calibrated in ways directly related to system performance. Key considerations include:

- System-level calibration is intended to ensure sensitivity, selectivity, continuity, and repeatability of each sensor to an acceptable system standard that is traceable and reproducible. This calibration is independent of geometrical considerations for normalization of the sensor output response for equivalent measurement over the short-term and long-term.

- Component-level calibration is intended to compensate the raw measurements for specific structural and geometrical configurations. This calibration is performed via a series of structurally and geometrically specific calibration curves from representative structural data.

- Internal calibration is intended to verify the functional integrity of the ASHMS unit and should be automatically incorporated into the fundamental design of the system. Specifically, given an input signal, the ASHMS should verify the integrity and fidelity of the imported signal data and the functional accuracy of the data processing function.

7.3.2 Utilization and Operation

Practical constraints on volume, weight, sensor response time, and capacity drive the size and configuration of the ASHMS. Specifically, this means that the type, number, location, and distribution of individual sensor elements are practically limited. Sensor configuration, in turn, directly influences the performance capabilities of the sensor network and the system's statistical probability of detection (POD) in terms of being able to accurately identify and characterize structural damage, degradation, flaws, and defects. A number of feasible technical solutions and operational approaches can be considered for achieving an ASHMS capability. However, regardless of the approach selected, it is imperative that the ASHMS design and configuration (e.g., selection of sensor type, number, and location) conform with the user's operations and support concepts, life-cycle structural integrity management philosophy, and host system capabilities.

ASHMS data set sizing limitations are a direct function of the number and type of sensors used, the sampling domain and rate for each sensor, the flight duration, and on-board data capacity and memory storage requirements. In other words, the sensor configurations used and the sampling profile can be tailored to accommodate relevant life cycle management criteria. In any event, however, it is critical that the sensors be placed at critical locations that will realistically and adequately provide indications of damage or structural degradation, as appropriate.

As the integrated structures undergo repair, in order to maintain the same level of internal interrogation (i.e., statistically identical POD), maintenance must be incorporated which allows for sensor repair, replacement, or alternatively, off-equipment inspection.

7.4 LIFE-CYCLE MANAGEMENT

Once the structural usage data has been acquired and collated, one must ask the question, "How will the data be used to make decisions regarding maintenance actions?" There are fundamentally two approaches that can be used to address this question: Life-cycle Aircraft Structural Health Management (LASHM) and Life Limits Management (LLM).

7.4.1 Life-cycle Aircraft Structural Health Management (LASHM)

LASHM involves analyzing, recording, and reporting data regarding the operational condition of a structural system in order to support decisions related to the operation and maintenance of the system. It includes the process of correlating acquired sensor data with operational and environmental conditions so as to develop a rational basis for fault diagnosis and condition analysis.

Technologies that may be used to support this approach can be divided into two basic categories: on-board (in-flight) sensory surveillance using an ASHMS technology platform, and ground-based NDE/I. From both a technical and operational perspective, on-board ASHMS is generally more desirable than ground-based NDE/I due to the operational need for dynamically assessing internal structural conditions during actual flight operations. Furthermore, embedded sensors are likely to yield a more comprehensive, realistic, and continuous measure of the structural integrity of the component over time.

With the use of increasingly more complex advanced material systems and aerospace structure designs, the focus for aircraft structural health management must go beyond the past emphasis on the instrumentation and avionics subsystems, into a robust, dynamic, and real-time assessment of structural integrity as related to damage or degradation. It is likely, however, that the health management philosophy for each of these conditions will be treated differently. Keeping in mind that the need exists to accommodate the data capacity, volume, weight, and TAT constraints for the aircraft, there are three primary management philosophies that might be employed for accomplishing aircraft structural maintenance.

- <u>Conventional Philosophy</u>. No data is acquired from an ASHMS platform. Assessment of the structural damage is made off-equipment using ground-based NDE/I equipment. This methodology does not give a dynamic measure of the structural usage or condition of the aircraft component, but may yield information related to structural damage when the extent of the damage is within the detectable range of the NDE/I equipment. It should be noted that effective implementation of this philosophy is predicated on the assumption that the NDE/I equipment is capable of detecting large area damage and degradation that exists within aerospace structures. In fact, as aircraft systems age, new structural integrity issues arise, and the state of the art for NDE/I often needs to be advanced to accommodate these issues.

- On-Condition Maintenance Philosophy. The on-condition maintenance philosophy is a performance-driven approach that is designed to facilitate dynamic detection, characterization, and mitigation of incipient structural damage and degradation (e.g., cracking, pitting, erosion, abrasion, punctures, disbonding, delamination, and impact damage) that adversely compromises aircraft performance or flightworthiness. ASHMS sensors are selected and located such that an assessment of the structural integrity of critical aircraft components is made during flight. In this scenario, a limited number of sensors are placed at critical locations to generate nearly continuous measurement of structural condition and damage in these locations during flight. This allows an historical record of the sensor readings, as correlated to inflight data recorder information, to be made. However, since the total number of sensors is limited, there is less than 100% interrogation coverage and structural damage to the aircraft may only be detected if its effect on the sensor measurement parameter is within the sensor sensitivity, dynamic range, and region of interest. In this case, since 100% coverage is not enabled, NDE/I activities are likely to be reduced, but not completely eliminated. (Although effective employment of an on-condition maintenance philosophy can nearly eliminate the reliance on ground-based NDE/I, the limited continuity of the ASHMS data stream will not enable a continuous historical record of structural usage and condition, as related to flight behavior and performance.)

7.4.2 Life Limits Management (LLM)

LLM is a fundamental maintenance concept predicated on assuring that an aircraft is totally flightworthy; i.e., capable of performing its intended operational mission without fault or failure. The LLM process is not unique to systems containing an ASHMS type platform. On the contrary, a coherent LLM process is utilized for every system that requires maintenance. The ASHMS platform does, however, afford the opportunity to accomplish LLM faster and more reliably, with reduced dependence on human input.

Reliable LLM requires an unbiased analysis, usually employing both theoretical and empirical modeling, of the expected behavior and performance of a structure under its intended operating environment. These parameters are initially determined during the research and development phase of a design program. The expected performance of a structure is modeled and tested under well-defined conditions and parameters, using specified engineering procedures and operational factors (e.g., anticipated stress profiles, thermomechanical fatigue, and environmental variations). This yields information that describes the factor limits on the material structure relative to specific failure modes. Also during the R&D phases, analyses are performed that describe and model the relevant fracture and failure mechanisms.

The aforementioned engineering testing and analysis usually provide the initial input used to determine the allowable limits that a given structure can safely withstand under specified operational conditions. However, during the life of the component, the allowable limits may change due to a number of factors, including:

- Changes in the engineering knowledge base used to develop the initial limits data.
- Effects of structural damage or degradation on the physical and functional integrity of the component that are not accounted for in the fail-safe design.
- Changes in the complexity and severity of the intended environmental and operational conditions.
- Effects of operational anomalies, environmental disturbances, or integrity perturbations that are not accounted for in the fail-safe design.

As previously mentioned, the LLM process does not require an ASHMS platform. In the absence of such a platform, the LLM process occurs in a static environment. The design, engineering, and test data is used to estimate the scheduled maintenance interval (i.e., the number of operational hours after which the structure should be removed from service) for periodic (i.e., scheduled) depot maintenance (PDM). However, secondary damage, faults, and failures may be induced during PDM or as the result of primary component failure. Consequently, the periodicity of the PDM may then be altered based on the lessons learned (e.g. predominating failures, failure modes, and presence of damage) during the PDM inspection and repair processes.

With the aid of an ASHMS platform, the LLM process occurs in a dynamic environment. The life limits information initially developed from design, engineering, and test data is continually updated as parametric analyses of the measured structural performance during flight is correlated and reconciled with the predicted structural performance. During the life cycle of the component, the analysis of actual versus expected performance can yield enhancements to the acceptable limits under which the system may perform. In addition, the acceptable limits derived during LLM can be updated to incorporate variations that are a function of inherent structural variability in terms of operational and environmental conditions, material properties, microstructural anomalies, and other systemic factors. This means that, with ASHMS, the LLM process is robust (the effect of actual performance conditions are measured and considered), dynamic (limits information may be updated nearly continually), and flexible (unintended variability is accounted for). ASHMS information can further extend LLM to allow automated control and recovery actions, in cases where safety of the flight is deemed by ASHMS to be in jeopardy.

7.5 MAINTENANCE PHILOSOPHY AND REPAIR STRATEGIES USING ASHMS

The operational use of ASHMS may offer unique opportunities for optimally refining the maintenance philosophy for maintaining aerospace structures. Moreover, the benefits that can be afforded by ASHMS are functionally dependent upon the maintenance philosophy that the airlines use. For example, some air carriers may elect to perform maintenance at their own operating location or at a depot. In this case, the ASHMS information could be used to analyze failure mechanisms and track structural anomalies throughout the life cycle of the aircraft. On the other hand, some air carriers may choose to have maintenance performed at off-site locations (for example, maintenance cost have driven several airlines to subcontract maintenance to domestic or overseas facilities). In this case, ASHMS information is less likely to be used for in-depth mechanistic analysis but solely as an identifier for likely regions of interest for repair.

Regardless of the maintenance philosophy selected or repair strategy implemented, it should also be noted that it may be necessary to repair or replace defective or failed components of the sensing system (e.g., the sensors or optical fibers) that generate the data input for ASHMS. With this in mind, it is important to consider the impact of repairs on the reliability of the sensing network, as input to the ASHMS. This can be accommodated in a number of ways.

- Replacement of Defective Sensor Components. For structural components that will be removed and replaced when maintenance is required, it is anticipated that the replacement components will contain new (replacement) sensing components such that configuration control is maintained (i.e., sensor type, location, size, and region of interrogation are the same for the replacement component as for the original component). This suggests that quality control and acceptance testing will be performed on the component (including its sensors) prior to use. Further, if the sensor system undergoes a system-level and component-level calibration to ensure that each sensor is properly referenced to the specified reference standards, additional calibration adjustments and compensations for replacement components and sensor variability may need to be made. For example, if, for a given component type, the microstructure of the replacement structural component in the vicinity of a fiber optic sensor is different than it was in the original component, it is likely that the sensor output response will change. In this case, the data provided to the ASHMS will reflect microstructural variations as well as erroneous indications of structural condition. While it is important to account for these anomalies at the microstructural level, independent analysis of each component may provide a baseline against which to standardize future performance.

- Direct Repair of Defective Sensor Components. Maintenance approaches may require direct repair of the sensor components during or after repair of a damaged module or component. While there are several mechanisms for direct repair of these components (e.g., fusion splicing for optical fibers), there is little research available on the impact that maintenance actions might have on the output response of the component. An additional effort to analyze the effect of this type of repair process, with the user's support, may be beneficial to help assess the impact on the ASHMS.

- Redundant Backup for Defective Sensor Components. In order to accommodate component failures in the ASHMS system without necessitating direct repair of the defective components, it is possible to incorporate, during the initial component manufacture, redundant system components located in the critical regions of the component. The type, configuration, and calibration of the components in the redundant system must be identical to those of the primary system. In the event there is a failure of a primary system component, one of the redundant components could be easily enabled. However, several issues must be considered if this design strategy is implemented. For example:

  – Adjacency effects (e.g., how does the presence of another sensor element within the region of interest influence the output response of the enabled sensor?) must be considered if the effective regions of interrogation are in close proximity. In this case, interference caused by close proximity of adjacent sensors may influence the data input to the ASHMS system. However, if the adjacent sensors are appropriately protected or calibrated to accommodate the proximity effects, signal misinterpretation may be avoided.

  – The redundant sensor design strategy also impacts cost. Although the cost benefits, tradeoffs, and impacts must be examined in detail for any given application, it is intuitive that the implementation of redundant sensors represents an obvious cost driver that must be considered.

- Disablement of Non-functioning Sensor Components. Since the ASHMS design requires appropriate data allocation to the database relative to the functionality of each sensor, it is possible to incorporate procedures by which specific defective components embedded within a critical region are automatically designated "non-functional" upon failure or malfunction. This information would then be loaded into the ASHMS database. While this approach has merit from a cost and resource management perspective, the primary impact, in terms of functional degradation of the ASHMS, lies in the reduced statistical confidence provided by the surviving (i.e., remaining usable) component suite. For example, reducing the number of active ASHMS sensor elements may adversely impact the confidence with which structural condition may be assessed and may (depending on the algorithms used for analysis) even provide misleading or erroneous results. Furthermore, current limitations in the practical size of most embedded sensor arrays is driven, in part, by the operational data capacity of the ASHMS. While the size of the sensor suite does still allow for some robustness, the cost-effective number of sensors does not allow complete component coverage, i.e., the sensors will not interrogate some regions. Consequently, further reducing the number of sensors below an acceptable reliability threshold may significantly impact the capability of the ASHMS.

7.6 FLIGHT CERTIFICATION

Prior to integration, implementation, and use of an ASHMS, it must undergo a rigorous process for acceptance by the FAA. This testing includes, but is not limited to design reviews and acceptance, loads analysis, stress analysis, and flight testing. Though it is beyond the scope of this work to comprehensively address the details of the certification process, it is a complex process which requires significant cooperation with the FAA. The details of the process used for flight certification vary depending upon the complexity and design of the ASHMS. For example, if the ASHMS is intended to control or otherwise impact flight operations, such as displaying health information to the aircrew inflight, a much more rigorous certification test is required.

7.7 MAINTENANCE CERTIFICATION

In general terms, maintenance certification is that process used to assure a system is capable of safely and reliably performing its intended function. For an aircraft system the goal is to assure continued flight-worthiness of the system. A distinction must be made between design certification, which is a part of the research and development process, versus maintenance certification, which occurs continually from flight to flight. Design certification involves development of systems to a degree that subsequent assemblies can be manufactured and operated without having to undergo the same degree of test or scrutiny. (The rigorous testing used for design certification of aircraft systems is intended to drive development efforts to achieve designs capable of extended reuse with no major failures between uses.) Maintenance certification involves processes that assure an aircraft system is ready and suitable for operational use.

An example of the second type of certification is the tracking and analysis of allowable operating constraints, performance and fatigue limits, and stress envelopes (hereinafter called life limits) for specific structural components. This analytical effort can be used to determine when components can remain in-service versus when these components should be removed for refurbishment, repair, or replacement based upon reported flight data relative to the life limits criteria. The purpose is to accumulate an adequate experience and knowledge base for determining and validating allowable life limits for components. In addition, low and high cycle life limits can be determined by monitoring and evaluating component operations and maintenance histories, including fleet leader components. This would provide a higher degree of safety and performance margin in the hardware, thereby contributing to greater reliability, availability, and useful service life.

For example, maintenance certification for many aircraft systems currently involves the use of ground-based NDE/I for assessing and verifying structural integrity and suitability for operational use. Although ground-based NDE/I equipment can indicate an abnormal degradation or deterioration of structural integrity or the presence of damage, failure, or defect conditions, these systems are not capable of determining the absolute source of a problem within the context of the operational and environmental conditions to which the aircraft have been subjected. Furthermore, these ground-based systems require manpower intensive methods, controlled facilities, and the use of expensive ancillary support and diagnostic equipment. In addition, ground-based evaluation and examination techniques typically involve significant intrusion (because of the need for direct access to structural components), the installation and use of ancillary support equipment and access kits, component teardown and disassembly, the purge of hazardous materials from fluid storage compartments, and component reassembly, testing, and verification.

Alternatively, on-board ASHMS systems, with an emphasis on supplemental ground-based data analysis, information feedback and reporting, and non-intrusive verification of systems integrity and function, could greatly reduce the technical risks, resource infrastructure, and cost associated with the use ground-based NDE/I systems. Furthermore, the use of ASHMS greatly minimizes the requirements for intrusive maintenance operations, expensive NDE/I equipment, and manpower intensive procedures, and inherently helps improve TAT, reduce MDT, and increase availability, readiness, and reusability.

7.8 OPERATIONAL RELIABILITY AND SUPPORTABILITY

Operational reliability and supportability are related. Generally speaking, operational reliability increases as component redundancy and complexity increases - even in those cases where there is little or no change in the mean time between failure (i.e., inherent reliability). However, supportability is usually degraded by the use of additional parts and increasing design complexity. This is because increased redundancy and complexity typically results in the increased potential for component failure. This, in turn, can lead to more unscheduled maintenance (thereby lowering MTBM and increasing O&S cost) and higher incidences of system intrusion (which in turn can increases the rate of induced failures, thereby further lowering MTBM). Thus, while a technically complex design approach may assure higher operational reliability for an aircraft system, this complexity can, in turn, result in significantly higher life-cycle cost due to the increased requirements for maintenance and related logistics support. (The reverse can also be true.)

This has important implications for aircraft design and maintenance certification. To be optimally effective, an aircraft fleet has to be reasonably free of operating and logistics constraints. This requires a high degree of demonstrated reliability. Consequently, a rigorous maintenance certification process based on the capabilities of ASHMS, is an affordable solution alternative for achieving this goal. This is because the aircraft fleet can be more accurately and responsively certified as flightworthy and capable of operating free of most constraints – irrespective of the predicted reliability or the experience base used to forecast this reliability.

Achieving increased operational reliability using the capabilities of an integrated ASHMS system offers two significant benefits. First, individual component or subsystem reliability is enhanced through the use of a more refined and structured maintenance certification process that is driven by the operational structural integrity information generated with ASHMS. Second, using ASHMS to achieve higher levels of demonstrated reliability offer opportunities for reducing system complexity while still assuring high mission reliability. Complexity, if reduced, means both a simpler and more integrated design with fewer and less complex components. In turn, simpler and more integrated designs manifest a much greater probability of operating for a longer period of time with fewer failures.

This is not to say that redundancy should be eliminated for critical systems. Disciplined and effective ASHMS-based maintenance certification procedures alone will not significantly change or impact the added complexity and redundancy that critical functions require. Rather, non-critical redundancy is reduced as a result of minimizing non-critical functional complexity. Although redundancy for criticality is still needed, there is a significant reduction in the number of components and subsystems that require this increased complexity. This does not affect mission reliability except to enhance it. Again, simplicity contributes to higher mission reliability through fewer opportunities for failure.

7.9 AVAILABILITY AND REVENUE

ASHMS offers the opportunity to significantly improve availability by reducing maintenance TAT and aircraft MDT. Though it is not quantitatively addressed in this study, it is important to note that the availability of an aircraft (i.e., the expected fraction of time that an aircraft will be ready to perform satisfactorily in an operating environment) is directly related to the revenue that a commercial air carrier can generate. This will likely significantly influence an airlines' financial capacity to implement an ASHMS capability. To adequately appreciate the significance of this statement, it is imperative to understand the that availability is inversely dependent upon the time required to maintain and support the system. In other words, as maintenance and support downtime increases, a system's availability decreases. Conversely, it can be stated that, for given levels of reliability, system availability can best be increased by decreasing maintenance and support downtime.

The critical consideration to keep in mind is this: **For any of these alternatives, the challenge is to determine at what point the required investment exceeds the return on investment.** For example, increasing support resources may not be a viable or desirable alternative if the resource expenditure is too great relative to the realized increase in availability (and associated increase in revenue).

The addition of an on-board ASHMS to an aircraft system may arguably be considered an addition of functional complexity, which would seem to contradict the goal of increasing system simplicity, affordability, reliability, and supportability. This assumption, however, overlooks the high reliability and capability associated with state-of-the-art ASHMS technologies and the inherent cost benefit through increased revenue and reduced support requirements of enhancing in-flight diagnostic and prognostic capabilities.

SECTION EIGHT

CONCLUSIONS AND RECOMMENDATIONS

In order for the integration of an advanced health monitoring system to be operationally effective, it must satisfactorily exhibit both operational benefits, such as safety improvement, and economic benefits. This study was performed to assess whether viable economic benefits could be realized from the introduction of health monitoring capability in selected aircraft structures. We also discussed other factors and benefits that might be realized with implementation of health monitoring. This study indicates that a significant reduction in the life cycle cost associated with maintaining and supporting structures could result in an operationally realistic return on investment. Specifically, if a 30-40% reduction in maintenance requirements is realized due to implementation and use of a health monitoring system, our analysis indicates that the time to recover the cost of the initial investment for both the engine mount and the trailing edge structure will be 2-3 years. However, due to the significantly larger area of the vertical stabilizer, the time to recover the investment associated with a health monitoring capability having a larger number of sensors, was determined to be 6-7 years.

Based on this analysis, we would recommend that the structures onto which a health monitoring capability is implemented be carefully selected such that economic viability could be realized. Both the engine mount and the trailing edge structure may be suitable candidates for health monitoring. However, since this study was limited to only three structures and only to the analysis of the life cycle cost associated with logistics and maintenance, it is recommended that further detailed cost analyses be performed to identify additional candidate structures for health monitoring. Ideally, subsequent analyses should include both logistics support cost and operating cost (such as the impact on operating revenue).

In addition, in order to fully realize the potential benefit of the health monitoring capability, it is imperative that the new capability be functionally integrated with revised maintenance processes, concepts, and procedures that would enable the use of health monitoring information, in a way that is commensurate with airline and FAA practices. To this end, we further recommend that a detailed analysis of the integration alternatives that would enable the new health monitoring capability be performed.

APPENDIX A

COST ELEMENT STRUCTURE

NASA HEALTH MONITORING SYSTEM TECHNOLOGY ASSESSMENT
STRUCTURES LIFE-CYCLE COST BENEFIT ANALYSIS MODEL
COST ELEMENT STRUCTURE (CES)
ACQUISTION COST ELEMENTS
PRODUCTION AND INSTALLATION START-UP
COMPONENT ACQUISITION COST
COMPONENT INSTALLATION COST
SUPPORT EQUIPMENT ACQUISITION
PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION
INITIAL TRAINING
TECHNICAL DOCUMENTATION
INITIAL SOFTWARE DEVELOPMENT
FACILITIES CONSTRUCTION AND MODIFICATION
INVENTORY INTRODUCTION
WARRANTY
CONTRACTOR SUPPORT
MISCELLANEOUS
LOGISTICS SUPPORT COST ELEMENTS
UNSCHEDULED MAINTENANCE LABOR COST
SCHEDULED MAINTENANCE LABOR COST
SUPPORT EQUIPMENT MAINTENANCE COST
TRAINING COST
UNSCHEDULED MAINTENANCE PARTS/MATERIALS COST
SCHEDULED MAINTENANCE PARTS/MATERIALS COST
UNSCHEDULED MAINTENANCE CONSUMABLES COST
SCHEDULED MAINTENANCE CONSUMABLES COST
SPARES REPLENISHMENT COST
TECHNICAL DOCUMENTATION REVISIONS COST
TRANSPORTATION COST
FACILITIES COST
ITEM MANAGEMENT COST
SOFTWARE MAINTENANCE COST
ENGINEERING CHANGES COST
WARRANTY COST
CONTRACTOR LOGISTICS SUPPORT COST
MISCELLANEOUS LOGISTICS SUPPORT COSTS

APPENDIX B

CASA MODEL OVERVIEW

APPENDIX B

CASA MODEL OVERVIEW

1.1 Background

The CASA model was derived from Honeywell's Total Resource and Cost Evaluation (TRACE) family of Logistics and Life-Cycle Cost Models. The TRACE family consists of several versions that range in complexity from TRACE 1 (least complex) to TRACE 5. CASA was actually formed from TRACE 2, but many of the features of TRACE 4 and 5 have since been added.

The economic scope of CASA covers the entire life cycle of a system, from its initial RDT&E costs to those associated with continuing recurring support and other related expenses incurred after the system is delivered. Basically, CASA works by using data entered by the user to calculate projected costs, evaluate sensitivities, compare alternatives, assess risk levels, and determine the probability of meeting LCC target values. CASA also offers a variety of analysis options and allows the user to tailor data inputs to assess the effects of these changes on the resultant LCC. At any point in the analysis, inputs may be saved and calculations may be made to that point for later evaluation. CASA can be used for a number of tasks, such as:

- LCC Estimates
- Logistics Trade Analyses
- Repair Level Analyses
- Production Rate and Quantity Analyses
- Warranty Analyses
- Spares Provisioning
- Resource Projections (e.g. manpower and support equipment)
- Risk and Uncertainty Analyses
- Cost Driver Sensitivity Analyses
- Reliability Growth Analyses
- Operational Availability Analyses
- Spares Optimization

Although not all of these functions were used in this CBA, they were available if such analysis were requested or required. If additional information on CASA is desired, the reader is referred to the CASA Users Manual for a detailed description of the capabilities listed above and their operation.

1.2 Capabilities

The CASA LCCM follows the classic approach of LCC estimating by aggregating and indenturing costs under the major categories of RDT&E costs, acquisition costs, and operations and support (O&S) costs. In addition, sensitivity and risk analyses can be quickly and accurately performed using CASA. Overall CASA cost estimating capabilities in each of these categories are described in the following subparagraphs.

- RDT&E: CASA computes several RDT&E cost subcategories, including costs for the following:
  - System/Project Management
  - System Test and Evaluation
  - Training
  - Data
  - Demonstration and Validation
  - Research and Development
  - Software
  - Other
- Acquisition Costs: CASA includes costs from the following subcategories when summing annual totals to determine the total acquisition cost:
  - Production Tooling and Test Equipment
  - Production Start-up
  - System Acquisition
  - System Shipping and Storage Containers

- Pre-Production Engineering
- Pre-Production Units Refurbished
- Installation
- Support Equipment
- Hardware Spares
- Spares Reusable Containers
- Technical Data
- Initial Training
- Training Devices
- New or Modified Facilities
- Initial Item Management
- Initial Software Development
- Miscellaneous Acquisition
- Warranty

- O&S Costs: The total O&S costs are the costs of operation, maintenance, and support of systems and SE at all applicable maintenance levels over the life of the system. CASA begins by estimating costs in the following subcategories over the classic three levels of maintenance (depot, intermediate, and organizational):
  - Operation Labor
  - Repair Labor
  - Support Equipment Maintenance
  - Recurring Training
  - Repair Parts and Materials
  - Repair Consumables

- Condemnation Spares Replenishment
- Technical Data Revisions
- Transportation
- Recurring Facilities
- Recurring Item Management
- Software Maintenance
- Contractor Services
- Engineering Changes
- Miscellaneous Operation and Support
- Recurring Warranty

In addition, CASA offers the user the flexibility to tailor data inputs to estimate the O&S costs associated with alternative maintenance concepts and multi-echelon levels of repair. Results for spares, SE, and manpower quantities are based on the maximum number of operating aircraft systems, while forecast maintenance actions are based on the average number. Further refinements in the calculations are possible by requesting output in constant, inflated, or inflated and discounted dollars.

- Sensitivity Analysis: The CASA Sensitivity Model provides a useful extension to the capabilities of the CASA LCCM. It performs sensitivity and multi-sensitivity analysis on several different input parameters, including relevant operational, R&M factors, and logistics support factors. This capability allows the user to measure the impact of changes in any of these key parameters on LCC and operational availability. Each parameter can be independently varied over a user-selected range of possible values, and the program will generate tables and graphs of the results. Five different sensitivity runs may be executed at one time for each input parameter.

APPENDIX C

LIFE-CYCLE COST MODEL EQUATIONS AND ALGORITHMS

NASA AIRCRAFT STRUCTURAL HEALTH MONITORING SYSTEM (ASHMS) TECHNOLOGY ASSESSMENT

LIFE-CYCLE COST BENEFIT ANALYSIS MODEL

GENERAL INPUT DATA - PROGRAMMATIC

COST FACTOR	NAME
INITIAL YEAR OF STUDY: The first year that the study is to address. The default value is 1999.	YRSTUDY
LIFE-CYCLE BASIS IN YEARS: The total number of years for which costs are to be computed. The default value is 20 years.	LCBASIS
FISCAL YEAR OF DOLLAR VALUES (BASE YEAR $): The base fiscal year in which all dollar amounts are to be expressed. The default value is 1999.	BY
AVERAGE NUMBER OF OPERATIONAL AIRCRAFT PER YEAR: The average number of authorized aircraft expected to be in operational use per year.	AVGSYS
AVERAGE NUMBER OF OPERATING LOCATIONS WITH MAINTENANCE CAPABILITY PER YEAR	LAVGLOC
AVERAGE NUMBER OF ORGANIC OPERATIONAL DEPOTS PER YEAR	DAVGLOC
AVERAGE NUMBER OF CONTRACTOR MAINTENANCE FACILITIES PER YEAR	CAVGLOC
AVERAGE FLYING HOURS PER YEAR PER AIRCRAFT: The average expected flying hours per year for an aircraft in operational use.	SOH

MAINTENANCE SUPPORT INPUT DATA

COST FACTOR	NAME
AVERAGE HOURLY MAINTENANCE LABOR RATE (MLR) - BASE YEAR $: The average hourly labor rate (in base year dollars per hour) for aircraft maintenance personnel. In addition to the direct labor rate, Include in this hourly labor rate the allocated costs associated with G&A, overhead, and other indirect costs.	MLR
AVERAGE HOURLY SOFTWARE MAINTENANCE LABOR RATE (SWLR) - BASE YEAR $. The average hourly labor rate (in base year dollars per hour) for software development and maintenance personnel. In addition to the direct labor rate, Include in this hourly labor rate the allocated costs associated with G&A, overhead, and other indirect costs.	SWLR
SUPPORT EQUIPMENT UTILIZATION (%) FACTOR (SEUF). SEUF is the average estimated percentage of time that the support equipment will be utilized relative to the average time that the SE is available for use. SEUF cannot be greater than 100% nor less than 0%. The default value is 100%.	SEUF
SPARES CONFIDENCE LEVEL (SCF). SCF is the probability of meeting all spares demands within the expected maintenance turnaround time. SCF is expressed as a proportional percentage less than or equal to 100%. (For example, an input of 90 implies that there is 90% confidence that a spare demand can be satisfied within the expected maintenance turnaround time.) The default value is 100%.	SCF

EARNED HOUR RATIO (EHR). EHR is the conversion factor for translating mean time to repair (expressed in manhours) into average total labor elapsed time. EHR must be greater than or equal to zero. The default value is 100%.	EHR
SUPPORT EQUIPMENT (SE) AVERAGE TOTAL UNIT COST (SCST) - BASE YEAR $. SCST is the average unit cost (in base year dollars) of all support equipment resources used at each maintenance location.	SCST
SE MAINTENANCE COST FACTOR (SEMANT). SEMANT is used to approximate the annual cost of maintaining and supporting the SE at each level of maintenance. SEMANT is expressed as a percentage of the SCST. SE maintenance costs are computed using the following equation by multiplying the SEMANT into the SCST in accordance with the following equation: SEMANT x SCST. The default value is 20%	SEMANT
RELIABILITY AND MAINTAINABILITY (R&M) INPUT DATA	
COST FACTOR	**NAME**
ITEM REPLACEMENT COST FACTOR. The cost factor used to estimate the replacement cost of an item. The cost factor is expressed as a percentage of the total annual maintenance costs (both unscheduled and scheduled) per maintenance action for the item. The default value is 200%	COST
ITEM QUANTITY PER AIRCRAFT: The number of items in each aircraft system	QPA
ITEM WEIGHT (in pounds)	WT
MEAN TIME BETWEEN UNSCHEDULED MAINTENANCE ACTIONS (MTBUMA): The average time in flight hours between unscheduled maintenance actions to correct (i.e., repair) item failures, defects, and malfunctions.	MTBUMA
UNSCHEDULED MAINTENANCE ACTIONS PER YEAR (UMA): UMA is the average number of unscheduled maintenance actions per year for the item. UMA is automatically calculated by multiplying the AVERAGE NUMBER OF OPERATIONAL AIRCRAFT PER YEAR by the AVERAGE FLYING HOURS PER YEAR PER AIRCRAFT and dividing by the MEAN TIME BETWEEN UNSCHEDULED MAINTENANCE ACTIONS for the item. Expressed as an equation: UMA = (AVSYS * SOH)/MTBUMA.	UMA
MEAN TIME (in manhours) TO REPAIR (MTTR) FOR UNSCHEDULED MAINTENANCE: MTTR is the average time, in total manhours, required to accomplish unscheduled maintenance (e.g., repair a failure or malfunction, accomplish an item overhaul, or recalibrate an item) on an item per unscheduled maintenance action. MTTR includes all on-equipment and off-equipment repair time, including item preparation, troubleshooting and testing, removal and replacement of parts, repair and calibration, overhaul and refurbishment, functional checks, etc.	MTTR
SCHEDULED AIRWORTHINESS CHECK FREQUENCIES AND INSPECTION INTERVALS. The required schedule interval, expressed in flight hours or months, between major checks and inspections for determining the airworthiness of an item. These schedule intervals are computed using structural inspection program specifications established by the air carrier. These specifications are normally based on manufacturer, FAA, and Maintenance Review Board (MRB) criteria, standards, and specifications. For intervals expressed in months, the input factor should be entered as an integer value less than 120 (i.e., ten years as an upper limit). For intervals expressed in flight hours, the input factor should be entered as an integer value greater than 120.	
Major checks (e.g., "C-Checks")	CCHECK
Accident damage (AD) structural inspections	ADSI
Environmental deterioration (ED) structural inspections	EDSI
Fatigue damage (FD) structural inspections	FDSI

Airworthiness Limitations Instructions (ALI) inspections	ALISI
SCHEDULED MAINTENANCE ACTIONS PER YEAR (SMA): SMA is the average number of scheduled maintenance actions per year for the item for each type of scheduled check or inspection. SMA is automatically computed for each inspection or check category by dividing the check interval basis (hours or months) into the utilization basis (flight hours per year or aircraft). For example, for checks computed on a flight hour basis, the equation is expressed in the following form: SMA = (AVSYS * SOH)/(CCHECK or ADSI or EDSI or FDSI or ALISI in flight hours)	
Major operational checks (e.g., "C-Checks")	CCSMA
Accident damage (AD) structural inspections	ADSMA
Environmental deterioration (ED) structural inspections	EDSMA
Fatigue damage (FD) structural inspections	FDSMA
Airworthiness Limitations Instructions (ALI) inspections	ALISMA
MEAN TIME (in manhours) FOR SCHEDULED MAINTENANCE (MTSM): MTSM is the average time, in manhours, required to accomplish scheduled maintenance on an item for each category of check or inspection. MTSM includes all on-equipment and off-equipment maintenance time needed to perform scheduled maintenance, including item preparation, NDE/NDI, troubleshooting and testing, diagnosis and prognosis, removal and replacement of parts, repair and calibration, overhaul and refurbishment, functional checks and tests, etc. MTSM does not include maintenance or supply delays.	
Major operational checks (e.g., "C-Checks")	CCMTSM
Accident damage (AD) structural inspections	ADMTSM
Environmental deterioration (ED) structural inspections	EDMTSM
Fatigue damage (FD) structural inspections	FDMTSM
Airworthiness Limitations Instructions (ALI) inspections	ALIMTSM
NOT REPARABLE THIS STATION (NRTS) RATE: NRTS is the expected percentage of time an item must be shipped to a specialized maintenance facility (e.g., contractor or manufacturer) for repairs, overhaul, or calibration. The default value is 1%.	NRTS
CONDEMNATION RATE (COND): COND is the expected percentage of time an item cannot be repaired and is subsequently condemned for disposal or salvage. The default value is 1%.	COND
RETEST OK (RTOK) RATE. RTOK is the percentage of time an item is removed from service for maintenance and subsequently checks serviceable during condition assessment. A serviceable condition is usually designated as “Retest OK (RTOK)” when diagnostics and testing cannot confirm the existence of a condition requiring corrective (i.e., repair) maintenance. The default value is 1%	RTOK
PROPORTIONALITY FACTOR FOR RTOK LABOR (PLRTOK): The average proportion of MTTR expended on items that RTOK, expressed as a percentage. The default value is 5%.	PLRTOK
AVERAGE MATERIAL COST PER REPAIR (MCPR): The average material cost required to accomplish unscheduled maintenance (i.e., repair a failure or malfunction) on an item.	MCPR
AVERAGE MATERIAL COST PER SCHEDULED MAINTENANCE ACTION (SMMCPA): The average material cost required to accomplish scheduled maintenance on an item.	SMMCPA

CONSUMABLE MATERIALS REPAIR COST FACTOR. The average cost of consumables (e.g., cleaners, swabs, solders, solvents, alcohol, etc) required to accomplish unscheduled maintenance (i.e., repair a failure or malfunction) of an item per unscheduled maintenance action, expressed as a percentage of MCPR. The default value is 5%.	CONSUM
CONSUMABLE MATERIALS SCHEDULED MAINTENANCE COST FACTOR. The average cost of consumables (e.g., cleaners, swabs, solders, solvents, alcohol, etc) required to accomplish scheduled maintenance (i.e., repair a failure or malfunction) of an item per scheduled maintenance action, expressed as a percentage of SMMCPA. The default value is 5%	SMCONS
TRANSPORTATION INPUT DATA	
COST FACTOR	**NAME**
TRANSPORTATION COST (BASE YEAR $) FOR SHIPPING THE ITEM TO THE REPAIR FACILITY (TPCOS). The average cost (in base year dollars) to transport an item between the removal location and the repair facility. This includes the costs associated with packaging, handling, storing, and shipping the item.	TPCOST
TRANSPORTATION COST (BASE YEAR $) FOR SHIPPING A NRTS ITEM A SPECIALIZED REPAIR FACILITY (TPCOSN). The average cost (in base year dollars) to transport an item that is NRTS to a specialized repair facility. This includes the costs associated with packaging, handling, storing, and shipping the item.	TPCOSN
TRAINING INPUT DATA	
COST FACTOR	**NAME**
ASSIGNED MAINTENANCE PERSONNEL: The average number of structures maintenance personnel assigned to each maintenance facility.	NOM
PERSONNEL TURNOVER RATE: The average annual turnover rate of maintenance personnel.	TOR
TRAINING HOURS REQUIRED FOR NEWLY ASSIGNED PERSONNEL: The average number of hours to properly train a new maintenance person.	TRHRS
AVERAGE ANNUAL TRAINING HOURS REQUIRED FOR REQUALIFICATION AND CONTINUATION TRAINING OF MAINTENANCE PERSONNEL: The average number of hours per year to provide requalification and continuation training for a maintenance person.	CTRHRS
TRAINING DEVELOPMENT/PRESENTATION COST (BASE YEAR $): The average cost per training hour for personnel, materials, travel, and other resources (in base year dollars) for developing, maintaining, and presenting training.	TRCOST
TECHNICAL DATA REVISION INPUT DATA	
COST FACTOR	**NAME**
AVERAGE TECHNICAL DATA REVISION PAGES PER YEAR: The average number of pages of technical data that will be revised each year for all maintenance facilities.	QTYRPG
AVERAGE REVISION COST PER PAGE: The average cost per page (in base year dollars) to develop and publish revision and change pages for technical data used at the maintenance facilities.	CSTRPG
SOFTWARE MAINTENANCE INPUT DATA	
COST FACTOR	**NAME**
MEAN TIME (in manhours) FOR SOFTWARE MAINTENANCE (MTSWM): The average annual manhours required to accomplish software maintenance at all maintenance facilities.	MTSWM

RECURRING FACILITIES INPUT DATA	
COST FACTOR	**NAME**
AVERAGE MAINTENANCE FACILITY FOOTPRINT (in square feet): The average number of floor square feet for each maintenance facility.	SQFT
AVERAGE RECURRING FACILITY COST (BASE YEAR $) PER SQUARE FOOT PER YEAR: The average annual cost per square foot (in base year dollars) for recurring facilities maintenance.	CSTSQFT
ITEM MANAGEMENT INPUT DATA	
COST FACTOR	**NAME**
AVERAGE NUMBER OF SPARE, REPAIR PART, AND OTHER MAINTENANCE STOCK ITEM TYPES MANAGED IN THE INVENTORY SYSTEM: The average number of of different types of spares, repair parts, and other maintenance stock items that are stocked in the inventory system at the maintenance facilities for use in the maintenance of aircraft structures.	QTYSP
AVERAGE ANNUAL INVENTORY MANAGEMENT COST (BASE YEAR$): The average annual cost (in base year dollars) to maintain a spare, repair part, or maintenance stock item type in the inventory management system.	IMCOST
AVERAGE QUANTITY OF SPARES, REPAIR PARTS, AND OTHER MAINTENANCE STOCK ITEMS THAT ARE STOCKED IN THE INVENTORY: The average quantity of spares, repair parts, and other maintenance stocks items that are stocked in the physical inventory at all maintenance facilities for use in the maintenance of aircraft structures.	QTYS
AVERAGE ANNUAL STOCKAGE COST (BASE YEAR$) PER STOCKED ITEM: The average annual cost (in base year dollars) to stock a spare, repair, or other maintenance stock item in the inventory at the maintenance facilities.	CSTSL
ENGINEERING CHANGES INPUT DATA	
COST FACTOR	**NAME**
AVERAGE ENGINEERING CHANGES IMPLEMENTED PER YEAR: The average number of engineering changes processed, evaluated, and implemented per year.	NYECP
AVERAGE COST (BASE YEAR $) FOR PROCESSING AND IMPLEMENTING ENGINEERING CHANGES: The average cost (in base year dollars) to process, analyze, and implement an engineering change. This includes the costs associated with engineering analysis, change proposal engineering evaluation and verification, change proposal administrative and contractual processing, retrofit kit development, and retrofit personnel, equipment, material, and related resource utilization.	ECPCST
WARRANTY INPUT DATA	
COST FACTOR	**NAME**
AVERAGE WARRANTY ACTIONS PER YEAR: The average number of warranty actions (e.g., warranty returns or warranty maintenance) per year for items that are warranted.	WA
YEARS OF WARRANTY COVERAGE: The number of years of remaining warranty coverage.	WAYRS
AVERAGE COST PER WARRANTY ACTION (BASE YEAR $): The average cost (in base year dollars) per warranty action. This includes the cost for sustaining, implementing, administering, and enforcing the warranty.	CSTWA

WARRANTY INPUT DATA

COST FACTOR	NAME
AVERAGE WARRANTY ACTIONS PER YEAR: The average number of warranty actions (e.g., warranty returns or warranty maintenance) per year for items that are warranted.	WA
YEARS OF WARRANTY COVERAGE: The number of years of remaining warranty coverage.	WAYRS
AVERAGE COST PER WARRANTY ACTION (BASE YEAR $): The average cost (in base year dollars) per warranty action. This includes the cost for sustaining, implementing, administering, and enforcing the warranty.	CSTWA

CONTRACTOR LOGISTICS SUPPORT INPUT DATA

COST FACTOR	NAME
AVERAGE CONTRACTOR LOGISTICS SUPPORT MANHOURS PER YEAR: The average number of contractor logistics support manhours required for maintenance support per year.	CLSMH
AVERAGE CONTRACTOR LOGISTICS SUPPORT COST PER MANHOUR (BASE YEAR $): The average cost (in base year dollars) per manhour for obtaining contractor logistics support services.	CLSCOST

MISCELLANEOUS LOGISTICS SUPPORT INPUT DATA

COST FACTOR	NAME
AVERAGE MISCELLANEOUS LOGISTICS SUPPORT COSTS PER YEAR (BASE YEAR $): The average miscellaneous costs in base year dollars for logistics support required per year.	MISCLSC

NASA AIRCRAFT STRUCTURAL HEALTH MONITORING SYSTEM (ASHMS) TECHNOLOGY ASSESSMENT

LIFE-CYCLE COST BENEFIT ANALYSIS MODEL

ACQUISITION COST INPUT DATA

COST FACTOR	NAME
NUMBER OF STRUCTURE: The total number of structures to have a health monitoring system (HMS) capability installed. Unless otherwise specified, the default value will be the number of average operational aircraft per year times the quantity per aircraft.	NHSS
PROCURED HMS COMPONENT QUANTITY: The total quantity of each HMS component to be procured for each structure. For sensors to be installed on a host structure, the procured quantity would be equal to the number of components per structure. For components installed on a per aircraft basis, for example the demodulator/signal processor and on-board data processor, enter the quantity per aircraft. For other components, enter a value that is equal to the intended or expected procurement quantity.	
Sensors per host system	SPCQ
Demodulator/Signal Processor	DPCQ
On-board Data Processors per host system	PPCQ
Data Transfer Unit (laptop or equivalent). The default value is the number of operating locations with maintenance facilities plus the number of organic depot facilities plus the number of contractor maintenance facilities. (Assumes one per facility.)	DTUPCQ
Remote Client Computers (remote clients to centralized server computer). The default value is the number of operating locations with maintenance facilities plus the number of organic depot facilities plus the number of contractor maintenance facilities.	CCPCQ
Centralized Server Computer (server to Remote client computers). The default value is the number of organic depots.	SCPCQ
Distributed LAN/WAN communications equipment and resources. The default value is the number of local operating locations with maintenance facilities plus the number of organic depots plus the number of contractor maintenance facilities.	LWPCQ
Software Development Hardware, Software, and Tools. The default value is the number of local operating locations with maintenance facilities plus the number of organic depots plus the number of contractor maintenance facilities.	SDPCQ

COMPONENT AVERAGE UNIT ACQUISITION COST (BASE YEAR $): The average unit cost (non-recurring) per procured component system in base year dollars associated with acquiring or developing each major technology component of the health monitoring system.	
Sensors	SUAC
Demodulator/Signal Processor	DUAC
On-board Data Processor	PUAC
Data Transfer Unit (laptop or equivalent)	DTUUAC
Remote Client Computers (remote clients to centralized server computer)	CCUAC
Centralized Server Computer (server to Remote client computers)	SCUAC
Distributed LAN/WAN	LWUAC
Software Development Hardware, Software, and Tools	SDUAC
PRODUCTION AND INSTALLATION START-UP (PISU) - BASE YEAR $: The average per unit non-recurring start-up cost (in base year dollars) associated with producing and installing the HMS components. This cost factor includes the costs associated with engineering analysis; generation of engineering drawings and data; engineering reviews and qualification testing; process and production engineering; and tooling, support equipment, facilities, and utilities development, modification, refurbishment, and retrofit. The cost is computed as a percentage of the average unit acquisition cost of each component using the PISU input factor. The default value for PISU is 5%.	PISU
Sensors	SPISU
Demodulator/Signal Processor	DPISU
On-board Data Processor	PPISU
Data Transfer Unit (laptop or equivalent)	DTUPISU
Remote Client Computers (remote clients to centralized server computer)	CCPISU
Centralized Server Computer (server to Remote client computers)	SCPISU
Distributed LAN/WAN	LWPISU
Software Development Hardware, Software, and Tools	SDPISU
COMPONENT AVERAGE UNIT INSTALLATION COST (BASE YEAR $): The average unit cost (non-recurring) per procured component system in base year dollars associated with installing, integrating, calibrating, testing, and certifying each major technology component of the health monitoring system. This cost factor includes the non-recurring average unit cost in base year dollars associated with the modification or retrofit of the host system required for the installation of each major technology component of the health monitoring system. It does NOT include the costs associated with production and installation start-up. The cost is computed as a percentage of the average unit acquisition cost of each component using the UIC input factor. The default value for PISU is 50%.	CUIC
Sensors	SUIC
Demodulator/Signal Processor	DUIC
On-board Data Processor	PUIC
Data Transfer Unit (laptop or equivalent)	DTUUIC

Remote Client Computers (remote clients to centralized server computer)	CCUIC
Centralized Server Computer (server to Remote client computers)	SCUIC
Distributed LAN/WAN	LWUIC
Software Development Hardware, Software, and Tools	SDUIC
NEW SUPPORT EQUIPMENT ACQUISITION COST (BASE YEAR $): The average total acquisition cost (non-recurring) for new support equipment required at each maintenance facility.	SECOST
PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION (PHS&T) COST (BASE YEAR $) FOR EACH LEVEL OF MAINTENANCE: The average per unit PHS&T cost (non-recurring) associated with supporting the production, delivery, and installation of HMS components into their host structures. The cost is computed as a percentage of the average unit acquisition cost of each component using the PHST input factor. The default value for PHST is 5%.	PHST
Sensors	SPHST
Demodulator/Signal Processor	DPHST
On-board Processor	PPHST
Data Transfer Unit (laptop or equivalent)	DTUPHST
Remote Client Computers (remote clients to centralized server computer)	CCPHST
Centralized Server Computer (server to Remote client computers)	SCPHST
Distributed LAN/WAN	LWPHST
Software Development Hardware, Software, and Tools	SDPHST
INITIAL TRAINING HOURS REQUIRED FOR NEWLY ASSIGNED PERSONNEL AT EACH LEVEL OF MAINTENANCE: The average number of hours required to provide initial (i.e., non-recurring) orientation and qualification training to each maintenance person assigned at each level of maintenance.	ITRGHRS
INITIAL TRAINING DEVELOPMENT/PRESENTATION COST PER TRAINING HOUR (BASE YEAR $): The average non-recurring cost per training hour (in base year dollars) for developing, maintaining, and presenting initial orientation and qualification training courses to maintenance personnel . This cost factor includes the costs associated with personnel (instructor), materials, training devices, travel, and other training resources.	ITCOST
AVERAGE PAGES OF NEW TECHNICAL DATA TO BE INITIALLY PRODUCED, GENERATED, OR PROCURED: The average number of pages of technical data to be initially (i.e., non-recurring) produced, generated, or procured for use at each maintenance facility.	QTYIPG
AVERAGE NON-RECURRING COST PER PAGE FOR PRODUCING NEW TECHNICAL DATA. The average non-recurring cost per page (in base year dollars) to develop and publish technical data to be used at the maintenance facilities. This cost factor includes the cost to print, collate, bind, punch holes, or otherwise prepare as a finished document the new technical data to be initially provided to each maintenance facility.	CSTIPG

INITIAL SOFTWARE DEVELOPMENT COST: The total average initial cost (i.e., non-recurring) for developing new software required for the production, installation, operation, and support of each HMS component. Only enter an input if this cost is not included in the unit acquisition cost for each HMS component	
Sensors	SSDC
Demodulator/Signal Processor	DSDC
On-board Processor	PSDC
Data Transfer Unit (laptop or equivalent)	DTUSDC
Remote Client Computers (remote clients to centralized server computer)	CCSDC
Centralized Server Computer (server to Remote client computers)	SCSDC
Distributed LAN/WAN	LWSDC
Software Development Hardware, Software, and Tools	SDSDC
AVERAGE FLOOR FOOTPRINT (in square feet) OF NEW FACILITY CONSTRUCTION REQUIRED: The average number of square feet associated with new facility construction for each maintenance facility.	NCSQFT
AVERAGE NON-RECURRING NEW FACILITY CONSTRUCTION COST (BASE YEAR $) PER SQUARE FOOT: The average non-recurring cost per square foot (in base year dollars) for new facilities construction at the maintenance facilities.	CSSQFT
AVERAGE FOOTPRINT (in square feet) OF FACILITY MODIFICATION, RENOVATION, OR REFURBISHMENT CONSTRUCTION: The average number of square feet associated with facility modification, renovation, or refurbishment construction for each maintenance facility.	MRSQFT
AVERAGE NON-RECURRING FACILITY MODIFICATION,RENOVATION, AND REFURBISHMENT COST (BASE YEAR $) PER SQUARE FOOT: The average non-recurring cost per square foot (in base year dollars) for facilities modification, renovation, and refurbishment at the maintenance facilities for each level of maintenance.	MRCSQFT
NUMBER OF NEW ITEMS TO BE INTRODUCED INTO THE INVENTORY MANAGEMENT SYSTEM: The average number of new inventory items (e.g., spare, repair parts, and other maintenance items) to be introduced into the inventory system as a result of the introduction of the new HMS capability.	IIIINTRO
NON-RECURRING ITEM INVENTORY INTRODUCTION COST (BASE YEAR$): The total non-recurring average cost (in base year dollars) to introduce new inventory items (e.g., spare, repair parts, and other maintenance items) into the inventory management system.	IIICST

NON-RECURRING WARRANTY PROCUREMENT COST: The average per unit non-recurring cost for developing, negotiating, and contractually implementing required component, subsystem, and system warranties associated with acquiring or developing each major technology component of the health monitoring system. The cost is computed as a percentage of the average unit acquisition cost of each component using the WPC input factor. The default value for WPC is 5%.	WPC
Sensors	SWPC
Demodulator/Signal Processor	DWPC
On-board Processor	PWPC
Data Transfer Unit (laptop or equivalent)	DTUWPC
Remote Client Computers (remote clients to centralized server computer)	CCWPC
Centralized Server Computer (server to Remote client computers)	SCWPC
Distributed LAN/WAN	LWWPC
Software Development Hardware, Software, and Tools	SDWPC
NON-RECURRING CONTRACTOR SUPPORT COST: The total non-recurring cost for obtaining contractor support services needed for acquiring or developing the health monitoring system.	ACSC
MISCELLANEOUS ACQUISITION COSTS: The total non-recurring miscellaneous costs associated with acquiring or developing the health monitoring system. These costs include all relevant costs not directly allocated to the above cost categories.	MAC

NASA AIRCRAFT STRUCTURAL HEALTH MONITORING SYSTEM (ASHMS) TECHNOLOGY ASSESSMENT

LIFE-CYCLE COST BENEFIT ANALYSIS MODEL

RECURRING LOGISTICS SUPPORT COST (LSC)

LSC COST ELEMENT	COST ESTIMATING RELATIONSHIP
MAINTENANCE LABOR COST (Unscheduled + Scheduled)	=B8+B10
Unscheduled Maintenance	=((UMA*MTTR*EHR*MLR)/(1+RTOK))*(1+(RTOK*PLRTOK))
Scheduled Maintenance	=SUM(B12:B16)
Major operational checks (e.g., "C-Checks")	=CCSMA*CCMTSM*EHR*MLR
Accident damage (AD) structural inspections	=ADSMA*ADMTSM*EHR*MLR
Environmental deterioration (ED) structural inspections	=EDSMA*EDMTSM*EHR*MLR
Fatigue damage (FD) structural inspections	=FDSMA*FDMTSM*EHR*MLR
Airworthiness Limitations Instructions (ALI) inspections	=ALISMA*ALIMTSM*EHR*MLR
MAINTENANCE PARTS AND MATERIALS COSTS (Unscheduled + Scheduled)	=B20+B22
Unscheduled Maintenance	=(UMA*(1-COND)*MCPR)/(1+RTOK)
Scheduled Maintenance	=((CCSMA+ADSMA+EDSMA+FDSMA+ALISMA)*(1-COND)*SMMCPA)
MAINTENANCE CONSUMABLES COSTS (Unscheduled + Scheduled)	=B26+B28
Unscheduled Maintenance	=MPMC*CONSUM
Scheduled Maintenance	=MPMCS*SMCONS
SUPPORT EQUIPMENT MAINTENANCE COST	=SCST*SEMANT*SEUF
TRAINING COST	=((NOM*(LAVGLOC+DAVGLOC+CAVGLOC))*TOR*TRHRS*MLR)+(NOM*(LAVGLOC+DAVGLOC+CAVGLOC)*CTRHRS*MLR)+((TRHRS+
SPARES REPLENISHMENT COST	=MLC*COND*COST
TECHNICAL DATA REVISIONS COST	=QTYRPG*CSTRPG
TRANSPORTATION COST	=((UMA+CCSMA+ADSMA+EDSMA+FDSMA+ALISMA)*(RTOK)*TPCOST)
FACILITIES COST	=SQFT*CSTSQFT*(LAVGLOC+DAVGLOC+CAVGLOC)
ITEM MANAGEMENT COST	=((QTYSP*IMCOST)+(QTYS*CSTSL))
SOFTWARE MAINTENANCE COST	=MTSWM*SWLR
ENGINEERING CHANGES COST	=NYECP*ECPCST
WARRANTY COST	=WA*CSTWA
CONTRACTOR LOGISTICS SUPPORT COST	=CLSMH*CLSCOST
MISCELLANEOUS LOGISTICS SUPPORT COSTS	=MISCLSC

NASA AIRCRAFT STRUCTURAL HEALTH MONITORING SYSTEM (ASHMS) TECHNOLOGY ASSESSMENT

LIFE-CYCLE COST BENEFIT ANALYSIS MODEL

ASHMS ACQUISITION COST RESULTS	
ACQUISTION COST ELEMENT	**COST ESTIMATING RELATIONSIP**
PRODUCTION AND INSTALLATION START-UP	=SUM(B6:B15)
Sensors	=SPISU*NHSS*SPCQ
Demodulator/Signal Processor	=DPISU*DPCQ*AVGSYS
On-board Data Processor	=PPISU*PPCQ*AVGSYS
Data Transfer Unit (laptop or equivalent)	=DTUPISU*DTUPCQ
Remote Client Computers (remote clients to centralized server	=CCPISU*CCPCQ
Centralized Server Computer (server to Remote client computers)	=SCPISU*SCPCQ
Distributed LAN/WAN	=LWPISU*LWPCQ
Software Development Hardware, Software, and Tools	=SDPISU*SDPCQ
COMPONENT ACQUISITION COST	=SUM(B17:B26)
Sensors	=SUAC*SPCQ*NHSS
Demodulator/Signal Processor	=DUAC*DPCQ*AVGSYS
On-board Data Processor	=PUAC*PPCQ*AVGSYS
Data Transfer Unit (laptop or equivalent)	=DTUUAC*DTUPCQ
Remote Client Computers (remote clients to centralized server	=CCUAC*CCPCQ
Centralized Server Computer (server to Remote client computers)	=SCUAC*SCPCQ

Distributed LAN/WAN	=LWUAC*LWPCQ
Software Development Hardware, Software, and Tools	=SDUAC*SDPCQ
COMPONENT INSTALLATION COST	=SUM(B28:B37)
Sensors	=SUIC*SPCQ*NHSS
Demodulator/Signal Processor	=DUIC*DPCQ*AVGSYS
On-board Data Processor	=PUIC*PPCQ*AVGSYS
Data Transfer Unit (laptop or equivalent)	=DTUUIC*DTUPCQ
Remote Client Computers (remote clients to centralized server	=CCUIC*CCPCQ
Centralized Server Computer (server to Remote client computers)	=SCUIC*SCPCQ
Distributed LAN/WAN	=LWUIC*LWPCQ
Software Development Hardware, Software, and Tools	=SDUIC*SDPCQ
SUPPORT EQUIPMENT ACQUISITION	=SECOST*(LAVGLOC+DAVGLOC+CAVGLOC)
PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION	=SUM(B41:B50)
Sensors	=SPHST*SPCQ*NHSS
Demodulator/Signal Processor	=DPHST*DPCQ*AVGSYS
On-board Data Processor	=PPHST*PPCQ*AVGSYS
Data Transfer Unit (laptop or equivalent)	=DTUPHST*DTUPCQ
computer)	=CCPHST*CCPCQ
Centralized Server Computer (server to Remote client computers)	=SCPHST*SCPCQ
Distributed LAN/WAN	=LWPHST*LWPCQ
Software Development Hardware, Software, and Tools	=SDPHST*SDPCQ

INITIAL TRAINING	=(((NOM*(LAVGLOC+DAVGLOC+CAVGLOC))*ITRGHRS*MLR)+(ITRGHRS*ITCOST))
TECHNICAL DATA	=QTYIPG*CSTIPG*(LAVGLOC+DAVGLOC+CAVGLOC)
INITIAL SOFTWARE DEVELOPMENT	=SUM(B56:B65)
Sensors	=SSDC
Demodulator/Signal Processor	=DSDC
On-board Data Processor	=PSDC
Data Transfer Unit (laptop or equivalent)	=DTUSDC
Remote Client Computers (remote clients to centralized server	=CCSDC
Centralized Server Computer (server to Remote client computers)	=SCSDC
Distributed LAN/WAN	=LWSDC
Software Development Hardware, Software, and Tools	=SDSDC
FACILITIES CONSTRUCTION AND MODIFICATION	=((NCSQFT*CSSQFT)+(MRSQFT*MRCSQFT))*(LAVGLOC+DAVGLOC+CAVGLOC)
INVENTORY INTRODUCTION	=IIIINTRO*IIICST
WARRANTY	=SUM(B71:B80)
Sensors	=SWPC*NHSS*SPCQ
Demodulator/Signal Processor	=DWPC*AVGSYS*DPCQ
On-board Data Processor	=PWPC*AVGSYS*PPCQ
Data Transfer Unit (laptop or equivalent)	=DTUWPC*DTUPCQ
Remote Client Computers (remote clients to centralized server	=CCWPC*CCPCQ
Centralized Server Computer (server to Remote client computers)	=SCWPC*SCPCQ

Distributed LAN/WAN	=LWWPC*LWPCQ
Software Development Hardware, Software, and Tools	=SDWPC*SDPCQ
CONTRACTOR SUPPORT	=ACSC
MISCELLANEOUS	250000

APPENDIX D

LOGISTICS SUPPORT COST FACTORS

GENERAL INPUT DATA - PROGRAMMATIC

Data Entry Legend:
Required Entry =
Optional Entry =
Default or Computed Entry (requires user input to override default value) =

COST FACTOR	NAME	VALUE
INITIAL YEAR OF STUDY: The first year that the study is to address. The default value is 1999.	YRSTUDY	1999
LIFE-CYCLE BASIS IN YEARS: The total number of years for which costs are to be computed. The default value is 20 years.	LCBASIS	20
FISCAL YEAR OF DOLLAR VALUES (BASE YEAR $): The base fiscal year in which all dollar amounts are to be expressed. The default value is 1999.	BY	1999
AVERAGE NUMBER OF OPERATIONAL AIRCRAFT PER YEAR: The average number of authorized aircraft expected to be in operational use per year.	AVGSYS	250
AVERAGE NUMBER OF OPERATING LOCATIONS WITH MAINTENANCE CAPABILITY PER YEAR	LAVGLOC	0
AVERAGE NUMBER OF ORGANIC OPERATIONAL DEPOTS PER YEAR	DAVGLOC	1
AVERAGE NUMBER OF CONTRACTOR MAINTENANCE FACILITIES PER YEAR	CAVGLOC	0
AVERAGE FLYING HOURS PER YEAR PER AIRCRAFT: The average expected flying hours per year for an aircraft in operational use.	SOH	3000

MAINTENANCE SUPPORT INPUT DATA		
Data Entry Legend:		
Required Entry =		
Optional Entry =		
Default or Computed Entry (requires user input to override default value) =		
COST FACTOR	**NAME**	**VALUE**
AVERAGE HOURLY LABOR RATE (BASE YEAR $) AT EACH LEVEL OF MAINTENANCE (MLR): The average hourly labor rate (in base year dollars per hour) of the aircraft maintenance personnel at each level of maintenance. In addition to the direct labor rate, Include in this hourly labor rate the allocated costs associated with G&A, overhead, and other indirect costs.	MLR	$95
AVERAGE SOFTWARE HOURLY LABOR RATE (BASE YEAR $) AT EACH LEVEL OF MAINTENANCE (SWLR). The average hourly labor rate (in base year dollars per hour) of the software development/maintenance personnel at each level of maintenance. In addition to the direct labor rate, Include in this hourly labor rate the allocated costs associated with G&A, overhead, and other indirect costs.	SWLR	$95
SUPPORT EQUIPMENT UTILIZATION FACTOR (SEUF) AT EACH LEVEL OF MAINTENANCE. SEUF is the average estimated percentage of time that the support equipment will be utilized relative to the average time that the SE is available for use. SEUF cannot be greater than 100% nor less than 0%. The default value is 100%.	SEUF	100%
SPARES CONFIDENCE LEVEL (SCF) AT EACH LEVEL OF MAINTENANCE. SCF is the probability of meeting all spares demands within the expected maintenance turnaround time. SCF is expressed as a proportional percentage less than or equal to 100%. (For example, an input of 90 implies that there is 90% confidence that a spare demand can be satisfied within the expected maintenance turnaround time.) The default value is 100%.	SCF	100%
Operating locations w/ maintenance capability	LSCF	100%
Organic operational depots	DSCF	100%
Contractor maintenance facilities	CSCF	100%
EARNED HOUR RATIO (EHR) AT EACH LEVEL OF MAINTENANCE. EHR is the conversion factor for translating mean time to repair (expressed in manhours) into average total labor elapsed time. EHR must be greater than or equal to zero. The default value is 100%.	EHR	100%
SUPPORT EQUIPMENT (SE) AVERAGE TOTAL UNIT COST (SCST) AT EACH LEVEL OF MAINTENANCE (BASE YEAR $). SCST is the average unit cost (in base year dollars) of all support equipment resources used at each location for each level of maintenance.	SCST	$796,875
SE MAINTENANCE COST FACTOR (SEMANT). SEMANT is used to approximate the annual cost of maintaining and supporting the SE at each level of maintenance. SEMANT is expressed as a percentage of the SCST. This factor usually has a value between 3% and 10%. SE maintenance costs are computed using the following equation by multiplying the SEMANT into the SCST in accordance with the following equation: SEMANT x SCST. The default value is 10%	SEMANT	20%

TRANSPORTATION INPUT DATA

	Data Entry Legend:	
	Required Entry =	
	Optional Entry =	
	Default Entry (requires user input to override default value) =	

COST FACTOR	NAME	VALUE
TRANSPORTATION COST (BASE YEAR $) FOR SHIPPING THE ITEM TO THE REPAIR FACILITY (TPCOS). The average cost (in base year dollars) to transport an item between the removal location and the repair facility. This includes the costs associated with packaging, handling, storing, and shipping the item.	TPCOST	$994
TRANSPORTATION COST (BASE YEAR $) FOR SHIPPING A NRTS ITEM TO THE REPAIR FACILITY (TPCOSN). The average cost (in base year dollars) to transport an item that is NRTS to the repair facility. This includes the costs associated with packaging, handling, storing, and shipping the item.	TPCOSN	$994

RECURRING TRAINING INPUT DATA

	Data Entry Legend:	
	Required Entry =	
	Optional Entry =	
	Default Entry (requires user input to override default value) =	

COST FACTOR	NAME	VALUE
ASSIGNED MAINTENANCE PERSONNEL: The average number of structures maintenance personnel assigned to each maintenance facility.	NOM	10
PERSONNEL TURNOVER RATE: The average annual turnover rate of maintenance personnel.	TOR	5%
TRAINING HOURS REQUIRED FOR NEWLY ASSIGNED PERSONNEL: The average number of hours to properly train a new maintenance person.	TRHRS	80
AVERAGE ANNUAL TRAINING HOURS REQUIRED FOR CONTINUATION TRAINING OF MAINTENANCE PERSONNEL: The average number of hours per year to provide continuation training for a qualified maintenance person.	CTRHRS	40
TRAINING DEVELOPMENT/PRESENTATION COST (BASE YEAR $): The average cost per year for personnel, materials, travel, and other resources (in base year dollars) for developing, maintaining, and presenting recurring training courses per class hour.	TRCOST	$420

TECHNICAL DATA REVISION INPUT DATA

Data Entry Legend:
Required Entry =
Optional Entry =
Default Entry (requires user input to override default value) =

COST FACTOR	NAME	VALUE
AVERAGE TECHNICAL DATA REVISION PAGES PER YEAR: The average number of pages of technical data that will be revised each year for all maintenance facilities.	QTYRPG	100
AVERAGE REVISION COST PER PAGE: The average cost per page (in base year dollars) to develop and publish revision and change pages for technical documents used at the maintenance facilities.	CSTRPG	$283

SOFTWARE MAINTENANCE INPUT DATA

Data Entry Legend:
Required Entry =
Optional Entry =
Default Entry (requires user input to override default value) =

COST FACTOR	NAME	VALUE
MEAN TIME (in manhours) FOR SOFTWARE MAINTENANCE (MTSWM): The average time, in manhours, per month required to accomplish software maintenance at all maintenance facilities.	MTSWM	14625

RECURRING FACILITIES INPUT DATA

Data Entry Legend:
Required Entry =
Optional Entry =
Default Entry (requires user input to override default value) =

COST FACTOR	NAME	VALUE
AVERAGE MAINTENANCE FACILITY FOOTPRINT (in square feet): The average number of floor square feet for each maintenance facility.	SQFT	5000
AVERAGE RECURRING FACILITY COST (BASE YEAR $) PER SQUARE FOOT PER YEAR: The average annual cost per square foot (in base year dollars) per year for recurring facilities maintenance.	CSTSQFT	$20

ITEM MANAGEMENT INPUT DATA

Data Entry Legend:		
Required Entry =		
Optional Entry =		
Default Entry (requires user input to override default value) =		
COST FACTOR	**NAME**	**VALUE**
AVERAGE NUMBER OF SPARE, REPAIR PART, AND OTHER MAINTENANCE STOCK ITEM TYPES MANAGED IN THE INVENTORY SYSTEM: The average number of of different types of spares, repair parts, and other maintenance stock items that are stocked in the inventory system at the maintenance facilities for use in the maintenance of aircraft structures.	QTYSP	200
AVERAGE ANNUAL INVENTORY MANAGEMENT COST (BASE YEAR$): The average annual cost (in base year dollars) to maintain a spare, repair part, or maintenance stock item type in the inventory management system.	IMCOST	$500
AVERAGE QUANTITY OF SPARES, REPAIR PARTS, AND OTHER MAINTENANCE STOCK ITEMS THAT ARE STOCKED IN THE INVENTORY: The average quantity of spares, repair parts, and other maintenance stocks items that are stocked in the physical inventory at all maintenance facilities for use in the maintenance of aircraft structures.	QTYS	1000
AVERAGE ANNUAL STOCKAGE COST (BASE YEAR$) PER STOCKED ITEM: The average annual cost (in base year dollars) to stock a spare, repair, or other maintenance stock item in the inventory at the maintenance facilities.	CSTSL	$500

ENGINEERING CHANGES INPUT DATA

Data Entry Legend:		
Required Entry =		
Optional Entry =		
Default Entry (requires user input to override default value) =		
COST FACTOR	**NAME**	**VALUE**
AVERAGE ENGINEERING CHANGES IMPLEMENTED PER YEAR: The average number of engineering changes processed, evaluated, and implemented per year.	NYECP	5
AVERAGE COST (BASE YEAR $) FOR PROCESSING AND IMPLEMENTING ENGINEERING CHANGES: The average cost (in base year dollars) to process, analyze, and implement an engineering change. This includes the costs associated with engineering analysis, change proposal engineering evaluation and verification, change proposal administrative and contractual processing, retrofit kit development, and retrofit personnel, equipment, material, and related resource utilization.	ECPCST	$100,000

CONTRACTOR LOGISTICS SUPPORT INPUT DATA

Data Entry Legend:
Required Entry =
Optional Entry =
Default Entry (requires user input to override default value) =

COST FACTOR	NAME	VALUE
AVERAGE CONTRACTOR LOGISTICS SUPPORT MANHOURS PER YEAR: The average number of contractor logistics support manhours required for maintenance support per year.	CLSMH	13867
AVERAGE CONTRACTOR LOGISTICS SUPPORT COST PER MANHOUR (BASE YEAR $) FOR EACH MAINTENANCE LEVEL: The average cost (in base year dollars) per manhour for obtaining contractor logistics support services.	CLSCOST	$65

APPENDIX E

SENSITIVITY FACTORS

NASA AIRCRAFT STRUCTURAL HEALTH MONITORING SYSTEM (ASHMS) TECHNOLOGY ASSESSMENT

LIFE-CYCLE COST BENEFIT ANALYSIS MODEL

LOGISTICS SUPPORT COST (LSC) SENSITIVITY FACTORS (used to approximate hypothetical changes in key sensitivity cost drivers as the result of the endowment of the item with a health monitoring system capability)

LSC SENSITIVITY FACTOR	NAME	VALUE
UNSCHEDULED MAINTENANCE ACTIONS (UMA). Used to vary the value of the unscheduled maintenance actions (UMA) cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of UMA entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFUMA1	90%
	SFUMA2	80%
	SFUMA3	70%
	SFUMA4	60%
	SFUMA5	50%
SCHEDULED MAINTENANCE ACTIONS (SMA). Used to vary the value of the scheduled maintenance actions (SMA) cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of SMA entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFSMA1	90%
	SFSMA2	80%
	SFSMA3	70%
	SFSMA4	60%
	SFSMA5	50%
MEAN TIME TO REPAIR FOR UNSCHEDULED MAINTENANCE (MTTR): Used to vary the value of the MTTR cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of MTTR entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFMTTR1	50%
	SFMTTR2	50%
	SFMTTR3	50%
	SFMTTR4	50%
	SFMTTR5	50%

MEAN TIME FOR SCHEDULED MAINTENANCE (MTSM): Used to vary the value of the MTSM cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of MTSM entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFMTSM1	50%
	SFMTSM2	50%
	SFMTSM3	50%
	SFMTSM4	50%
	SFMTSM5	50%
RETEST OK (RTOK) RATE. Used to vary the value of the RTOK cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of RTOK entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFRTOK1	100%
	SFRTOK2	100%
	SFRTOK3	100%
	SFRTOK4	100%
	SFRTOK5	100%
SUPPORT EQUIPMENT UTILIZATION FACTOR (SEUF). Used to vary the value of the SEUF cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of SEUF entered in the Maintenance Support Input worksheet. Up to five sensitivity values can be entered.		
	SFSEUF1	90%
	SFSEUF2	80%
	SFSEUF3	75%
	SFSEUF4	50%
	SFSEUF5	25%
SUPPORT EQUIPMENT (SE) AVERAGE TOTAL UNIT COST (SCST). Used to vary the value of the SCST cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of SCST entered in the Maintenance Support Input worksheet. Up to five sensitivity values can be entered.		
	SFSCST1	90%
	SFSCST2	80%
	SFSCST3	75%
	SFSCST4	50%
	SFSCST5	25%
AVERAGE MATERIAL COST PER REPAIR (MCPR). Used to vary the value of the MCPR cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of MCPR entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFMCPR1	50%
	SFMCPR2	50%
	SFMCPR3	50%
	SFMCPR4	50%

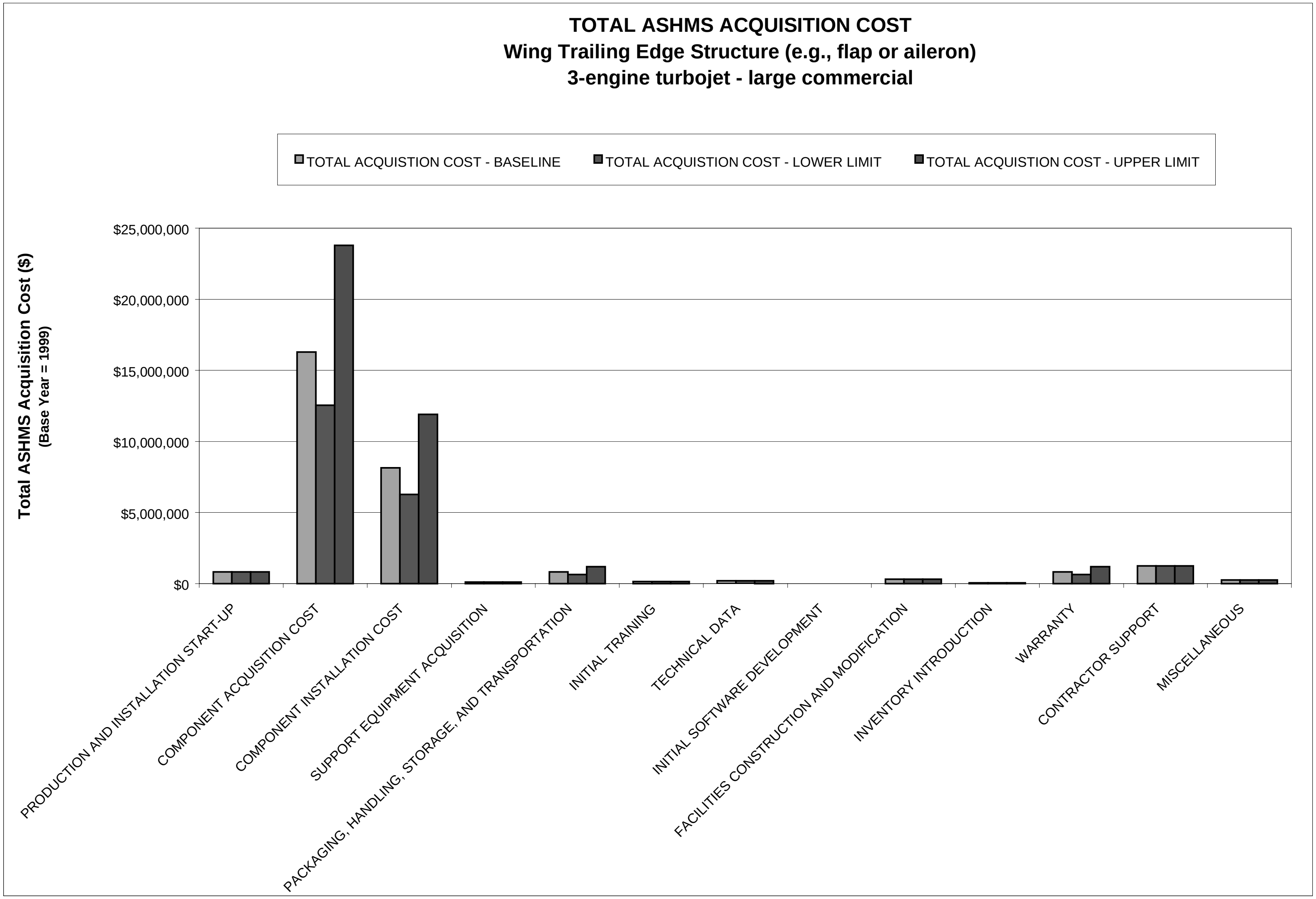
	SFMCPR5	50%
AVERAGE MATERIAL COST PER SCHEDULED MAINTENANCE ACTION (SMMCPA). Used to vary the value of the SMMCPA cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of SMMCPA entered in the R&M Input worksheet. Up to five sensitivity values can be entered.		
	SFSMMCPA1	50%
	SFSMMCPA2	50%
	SFSMMCPA3	50%
	SFSMMCPA4	50%
	SFSMMCPA5	50%
AVERAGE MAINTENANCE FACILITY FOOTPRINT in square feet (SQFT): Used to vary the value of the SQFT cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of SQFT entered in the Facilities Input worksheet. Up to five sensitivity values can be entered.		
	SFSQFT1	120%
	SFSQFT2	120%
	SFSQFT3	120%
	SFSQFT4	120%
	SFSQFT5	120%
MEAN TIME (in manhours) FOR SOFTWARE MAINTENANCE (MTSWM): Used to vary the value of the MTSWM cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of MTSWM entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFMTSWM1	80%
	SFMTSWM2	80%
	SFMTSWM3	80%
	SFMTSWM4	80%
	SFMTSWM5	80%
AVERAGE NUMBER OF SPARE, REPAIR PART, AND OTHER MAINTENANCE STOCK ITEM TYPES MANAGED IN THE INVENTORY SYSTEM: Used to vary the value of the QTYSP cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of QTYSP entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFQTYSP1	120%
	SFQTYSP2	120%
	SFQTYSP3	120%
	SFQTYSP4	120%
	SFQTYSP5	120%

AVERAGE QUANTITY OF SPARES, REPAIR PARTS, AND OTHER MAINTENANCE STOCK ITEMS THAT ARE STOCKED IN THE INVENTORY: Used to vary the value of the QTYS cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of QTYS entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFQTYS1	90%
	SFQTYS2	80%
	SFQTYS3	70%
	SFQTYS4	60%
	SFQTYS5	50%
AVERAGE TECHNICAL DATA REVISION PAGES PER YEAR: Used to vary the value of the QTYRPG cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of QTYRPG entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFQTYRPG1	120%
	SFQTYRPG2	120%
	SFQTYRPG3	120%
	SFQTYRPG4	120%
	SFQTYRPG5	120%
TRAINING HOURS REQUIRED FOR NEWLY ASSIGNED PERSONNEL AT EACH LEVEL OF MAINTENANCE: Used to vary the value of the TRHRS cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of TRHRS entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFTRHRS1	120%
	SFTRHRS2	120%
	SFTRHRS3	120%
	SFTRHRS4	120%
	SFTRHRS5	120%
AVERAGE ANNUAL TRAINING HOURS REQUIRED FOR CONTINUATION TRAINING OF MAINTENANCE PERSONNEL: Used to vary the value of the CTRHRS cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of CTRHRS entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFCTRHRS1	120%
	SFCTRHRS2	120%
	SFCTRHRS3	120%
	SFCTRHRS4	120%
	SFCTRHRS5	120%
AVERAGE CONTRACTOR LOGISTICS SUPPORT MANHOURS PER YEAR: Used to vary the value of the CLSMH cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of CLSMH entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFCLSMH1	90%

	SFCLSMH2	80%
	SFCLSMH3	70%
	SFCLSMH4	60%
	SFCLSMH5	50%
AVERAGE ENGINEERING CHANGES IMPLEMENTED PER YEAR: Used to vary the value of the NYECP cost factor for the purpose of measuring the impact of changes in this parameter. The value of the sensitivity factor is expressed as a percentage change in the baseline values of NYECP entered in the Software Maintenance Input worksheet. Up to five sensitivity values can be entered.		
	SFNYECP1	120%
	SFNYECP2	120%
	SFNYECP3	120%
	SFNYECP4	120%
	SFNYECP5	120%

APPENDIX F

ASHMS ACQUISITION COST


TOTAL ASHMS ACQUISITION COST
Wing Trailing Edge Structure (e.g., flap or aileron)
3-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
$25,000,000
$20,000,000
$15,000,000
$10,000,000
$5,000,000
$0
PRODUCTION AND INSTALLATION START-UP
COMPONENT ACQUISITION COST
COMPONENT INSTALLATION COST
SUPPORT EQUIPMENT ACQUISITION
PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION
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INITIAL SOFTWARE DEVELOPMENT
FACILITIES CONSTRUCTION AND MODIFICATION
INVENTORY INTRODUCTION
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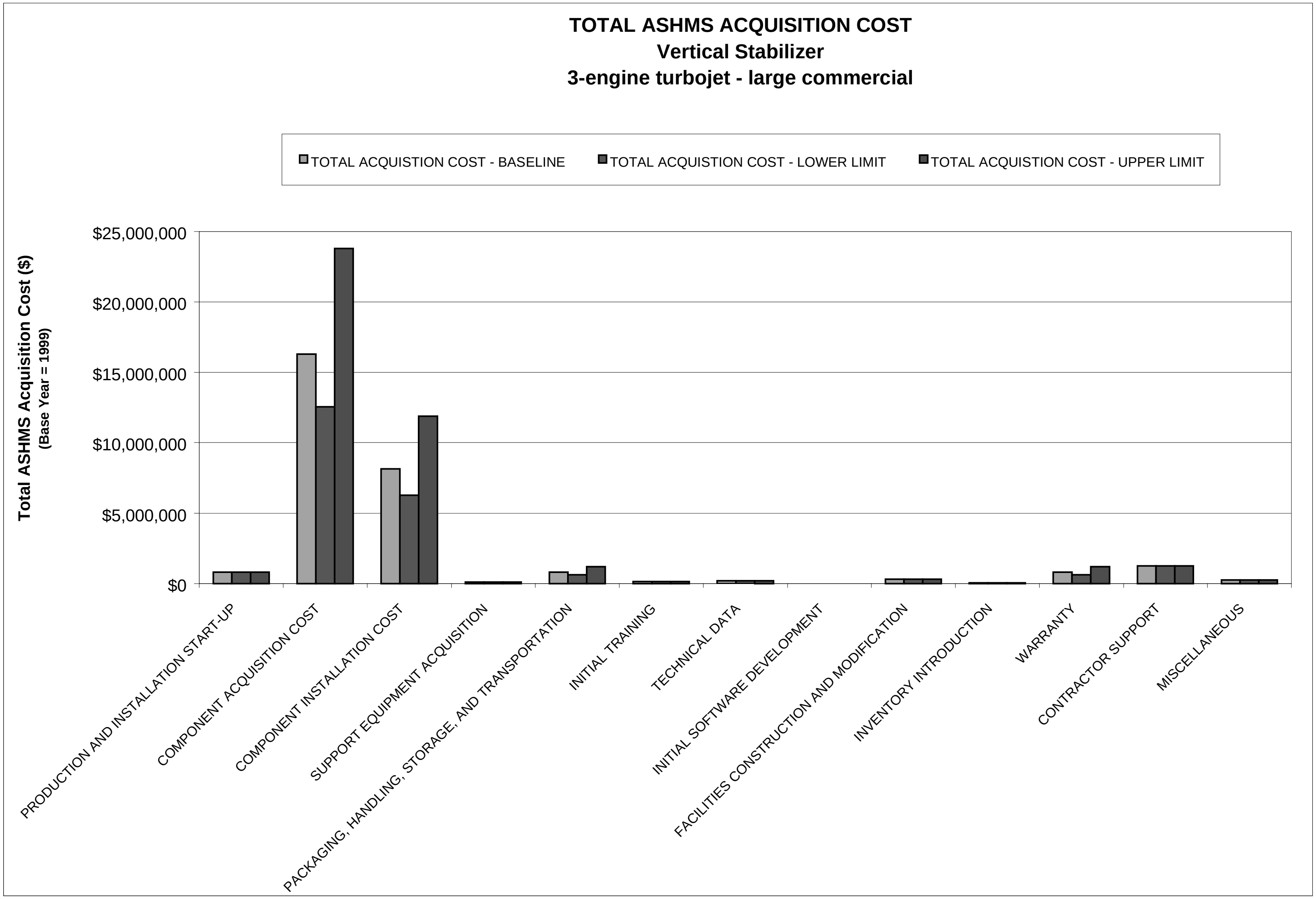
CONTRACTOR SUPPORT
MISCELLANEOUS



TOTAL ASHMS ACQUISITION COST
Vertical Stabilizer
3-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
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$20,000,000
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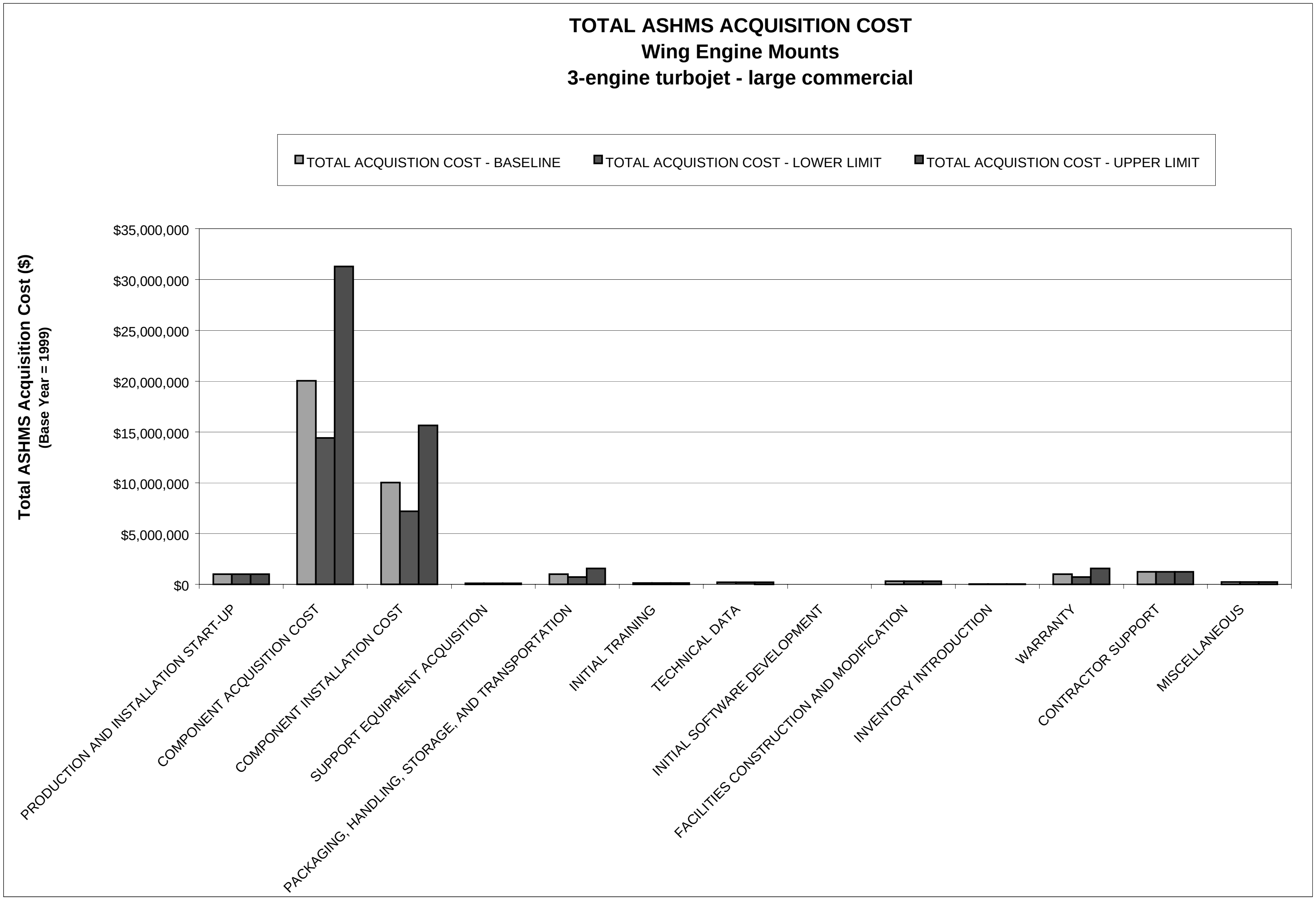

TOTAL ASHMS ACQUISITION COST
Wing Engine Mounts
3-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
$35,000,000
$30,000,000
$25,000,000
$20,000,000
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$0
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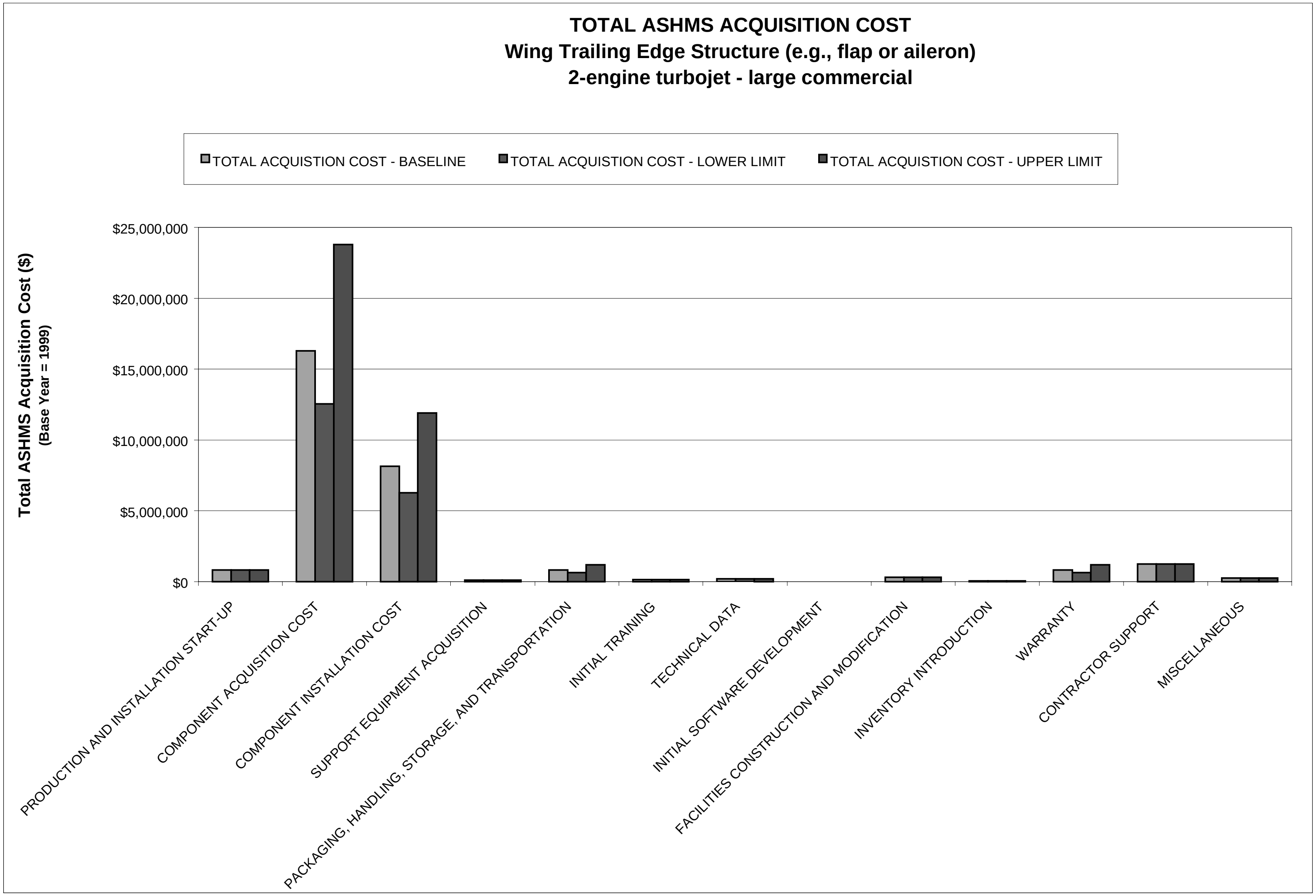

TOTAL ASHMS ACQUISITION COST
Wing Trailing Edge Structure (e.g., flap or aileron)
2-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
$25,000,000
$20,000,000
$15,000,000
$10,000,000
$5,000,000
$0
PRODUCTION AND INSTALLATION START-UP
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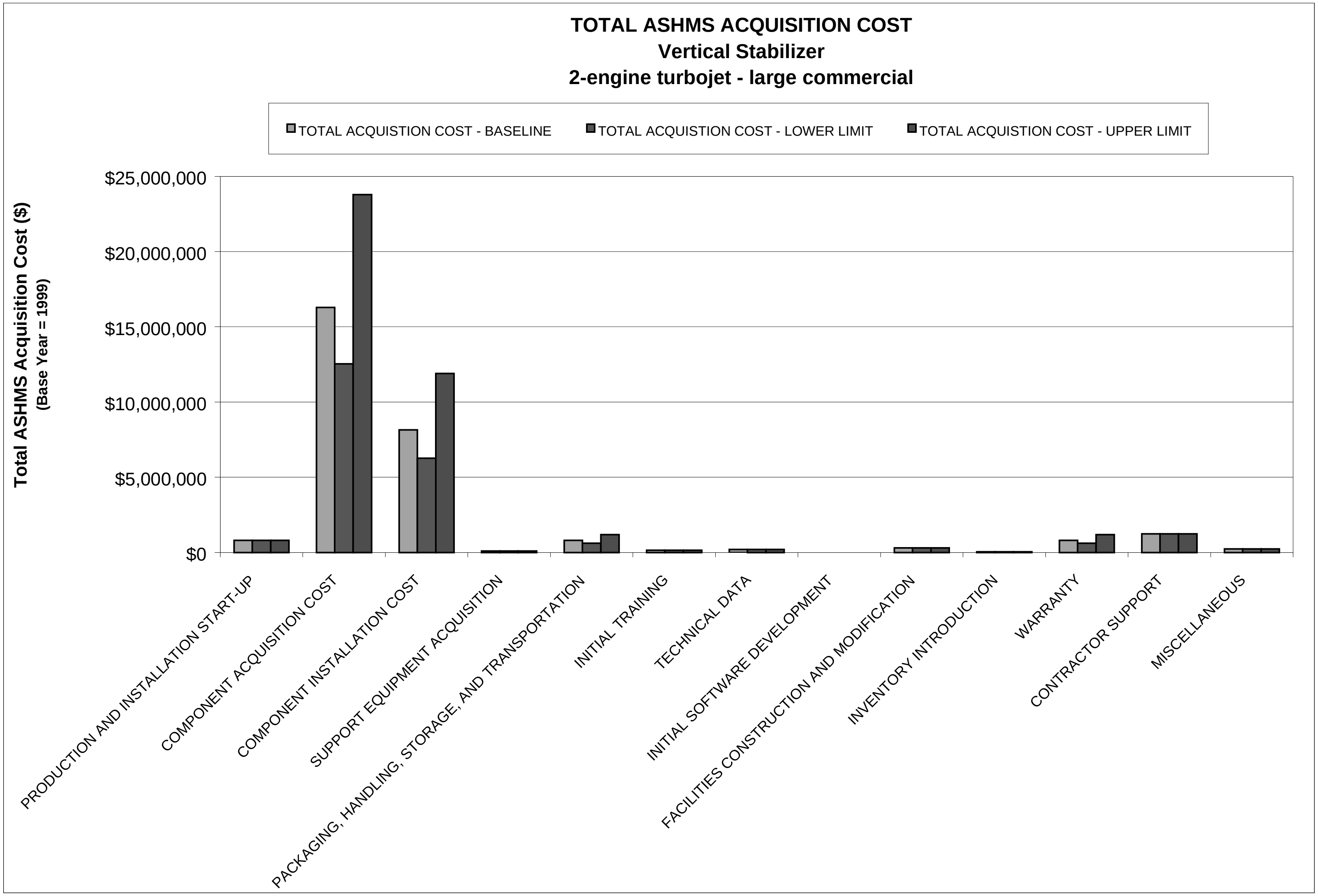
TOTAL ASHMS ACQUISITION COST
Vertical Stabilizer
2-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
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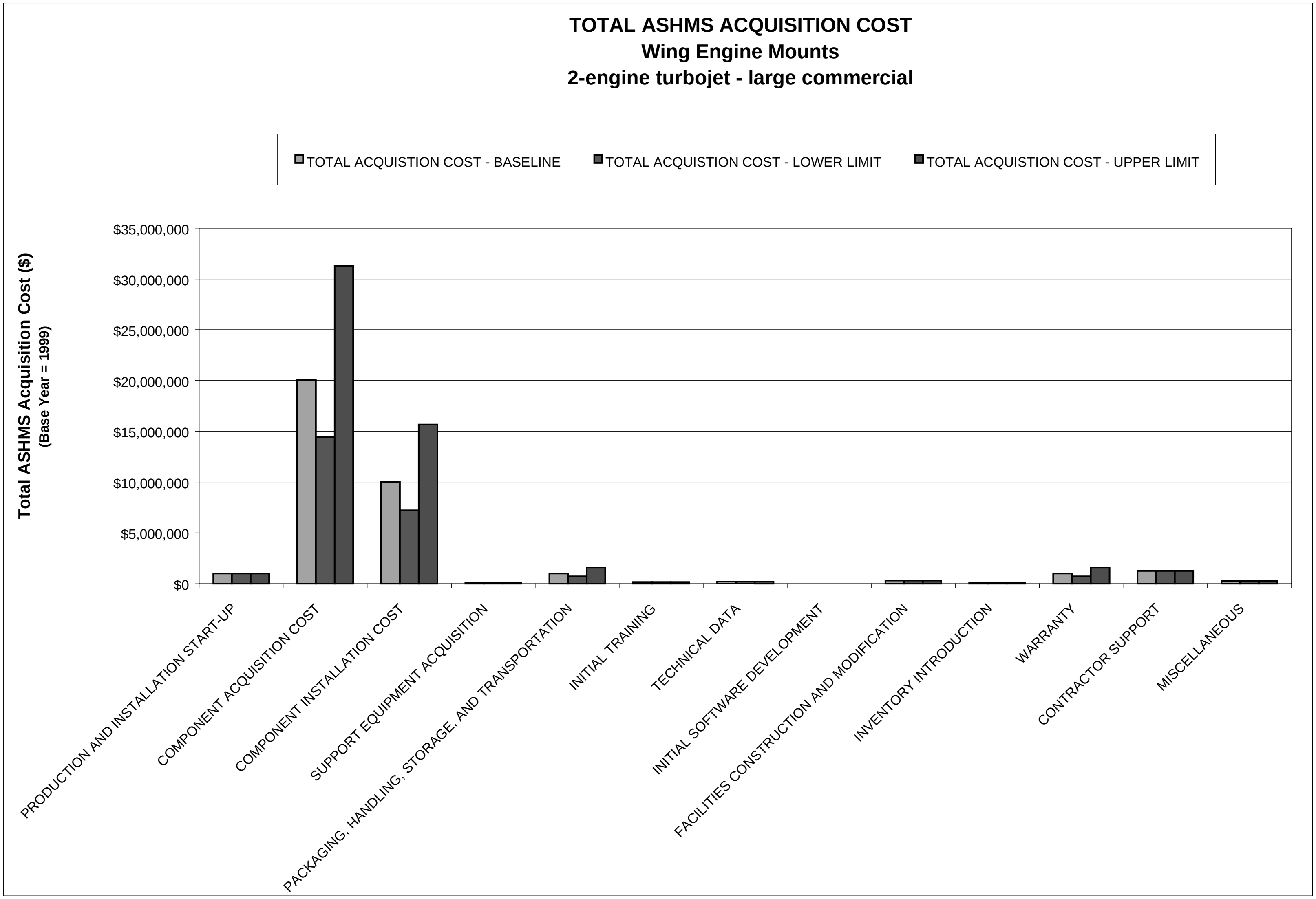
TOTAL ASHMS ACQUISITION COST
Wing Engine Mounts
2-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
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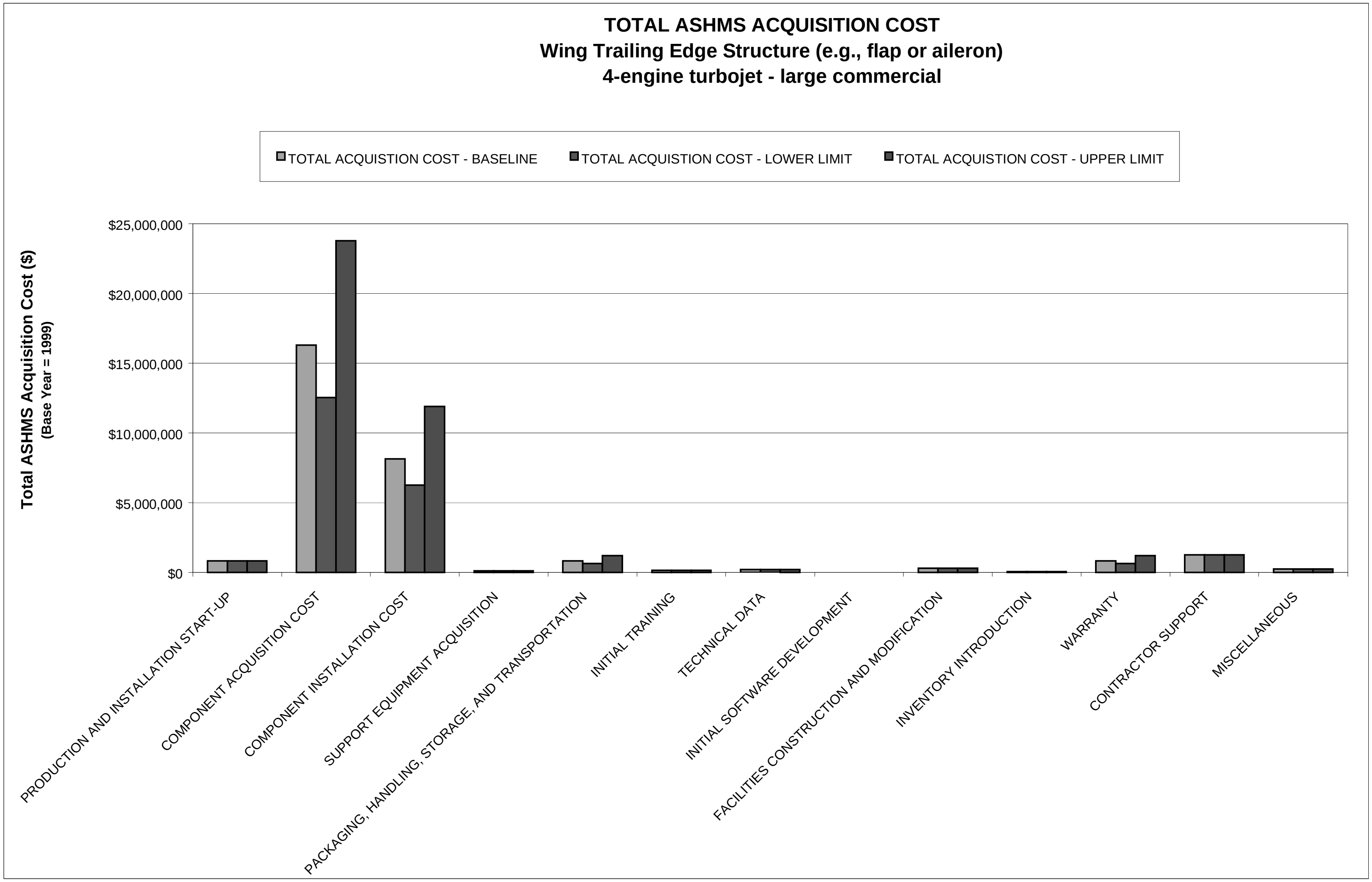

TOTAL ASHMS ACQUISITION COST
Wing Trailing Edge Structure (e.g., flap or aileron)
4-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
$25,000,000
$20,000,000
$15,000,000
$10,000,000
$5,000,000
$0
PRODUCTION AND INSTALLATION START-UP
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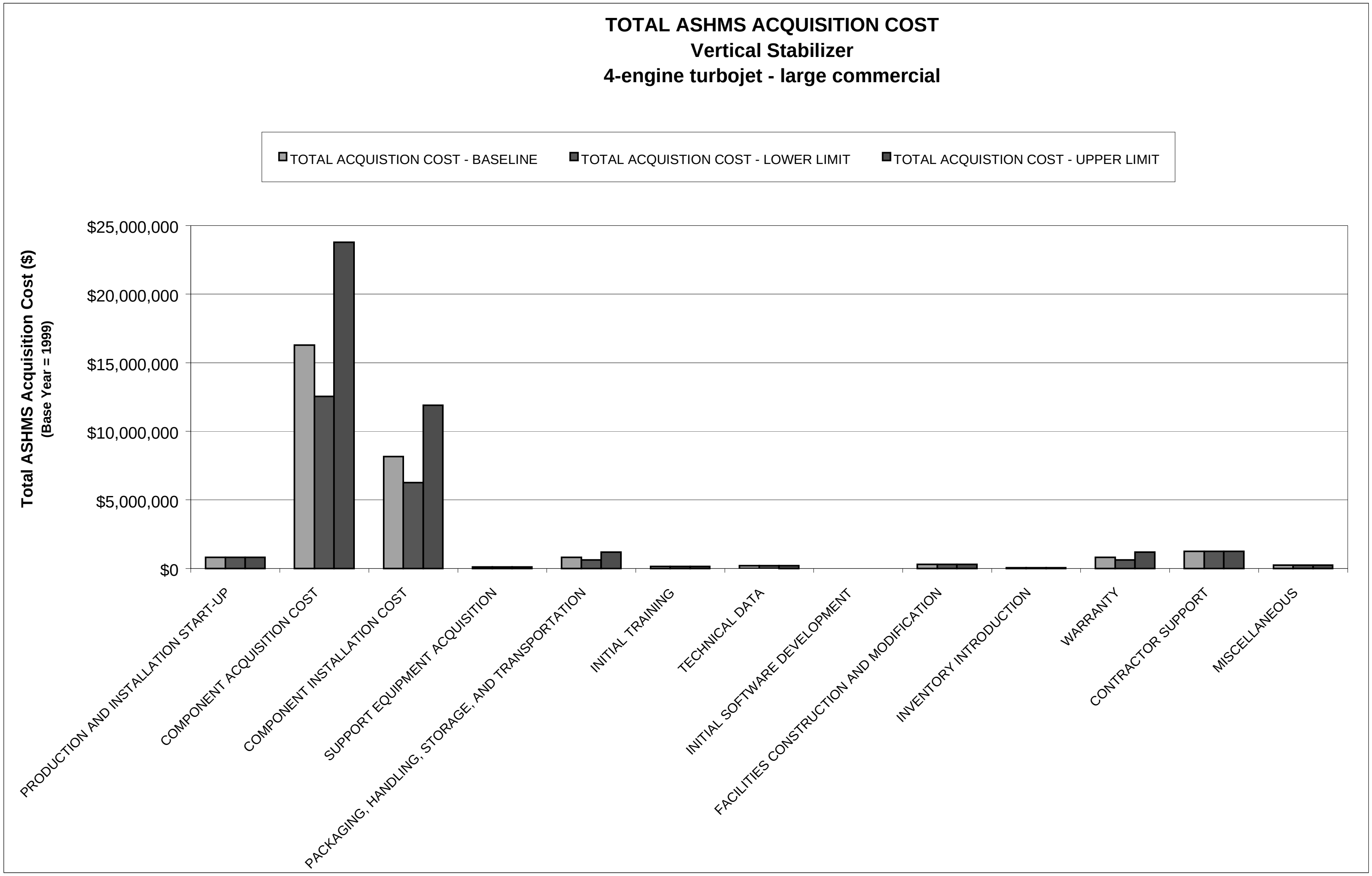
TOTAL ASHMS ACQUISITION COST
Vertical Stabilizer
4-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
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$20,000,000
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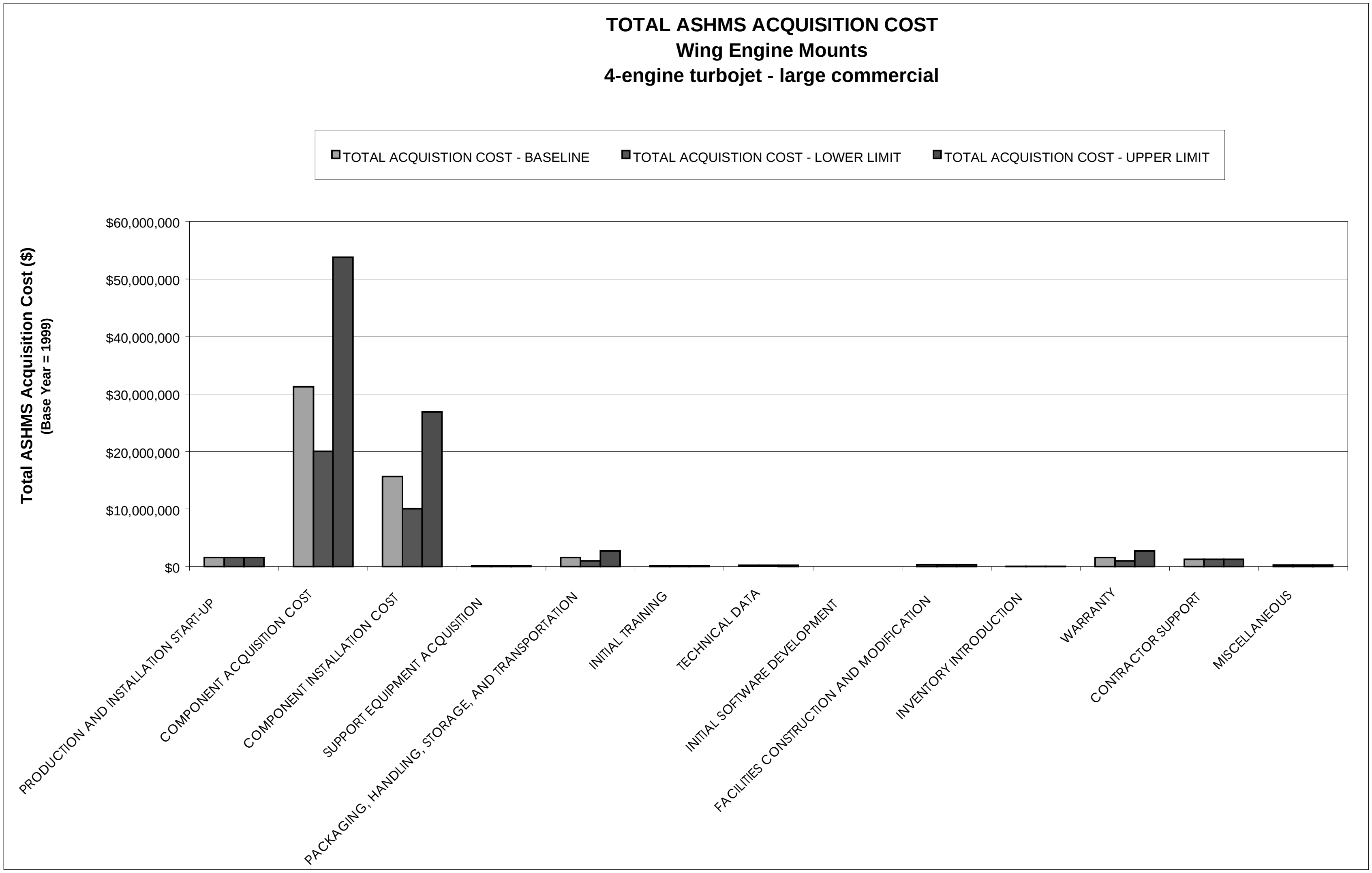
TOTAL ASHMS ACQUISITION COST
Wing Engine Mounts
4-engine turbojet - large commercial
TOTAL ACQUISTION COST - BASELINE
TOTAL ACQUISTION COST - LOWER LIMIT
TOTAL ACQUISTION COST - UPPER LIMIT
Total ASHMS Acquisition Cost ($)
(Base Year = 1999)
$60,000,000
$50,000,000
$40,000,000
$30,000,000
$20,000,000
$10,000,000
$0
PRODUCTION AND INSTALLATION START-UP
COMPONENT ACQUISITION COST
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The subject of sensor-based structural health monitoring is very diverse and encompasses a wide range of activities including initiatives and innovations involving the development of advanced sensor, signal processing, data analysis, and actuation and control technologies. In addition, it embraces the consideration of the availability of low-cost, high-quality contributing technologies, computational utilities, and hardware and software resources that enable the operational realization of robust health monitoring technologies.
This report presents a detailed analysis of the cost benefit and other logistics and operational considerations associated with the implementation and utilization of sensor-based technologies for use in aerospace structure health monitoring. The scope of this volume is to assess the economic impact, from an end-user perspective, implementation health monitoring technologies on three structures. It specifically focuses on evaluating the impact on maintaining and supporting these structures with and without health monitoring capability.

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