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Demonstration of a Probabilistic Technique for the Determination of Economic Viability of Very Large Transport Configurations

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Executive Summary

Over the past few years, modern aircraft design has experienced a paradigm shift from designing for performance to designing for affordability. This report contains a probabilistic approach that will allow traditional deterministic design methods to be extended to account for disciplinary, economic, and technological uncertainty. The probabilistic approach was facilitated by the Fast Probability Integration (FPI) technique; a technique which allows the designer to gather *valuable* information about the vehicle's behavior in the design space. This technique is efficient for assessing multi-attribute, multi-constraint problems in a more realistic fashion. For implementation purposes, this technique is applied to illustrate how both economic and technological uncertainty associated with a Very Large Transport aircraft concept may be assessed. The assessment is evaluated with the FPI technique to determine the cumulative probability distributions of the design space, as bound by economic objectives and performance constraints. These distributions were compared to established targets for a comparable large capacity aircraft, similar in size to the Boeing 747-400. The conventional baseline configuration design space was determined to be unfeasible and marginally viable, motivating the infusion of advanced technologies, including reductions in drag, specific fuel consumption, wing weight, and Research, Development, Testing, and Evaluation costs. The resulting system design space was qualitatively assessed with technology metric "k" factors. The infusion of technologies shifted the VLT design into regions of feasibility and greater viability. The study also demonstrated a method and relationship by which the impact of new technologies may be assessed in a more system focused approach.

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List of Acronyms

$/RPM	Average Required Yield per Revenue Passenger Mile
Acq $	Acquisition Price
ALCCA	Aircraft Life Cycle Cost Analysis
AMV+	Advanced Mean Value +
ANOVA	Analysis of Variance
AR	Aspect Ratio
ASDL	Aerospace Systems Design Laboratory
B747-400	Boeing 747-400 Aircraft
CDF	Cumulative Distribution Function
DoE	Design of Experiments
EPA	Environmental Protection Agency
FAR	Federal Aviation Regulations
FLOPS	Flight Optimization System
FPI	Fast Probability Integration
FY	Fiscal Year
HT	Horizontal Tail
IHPTET	Improved High Pressure Turbine Engine Technology
LDGFL	Landing Field Length
LSF	Limit State Function
MPP	Most Probable Point
RDTE	Research, Development, Testing, and Evaluation
ROI	Return on Investment
RSE	Response Surface Equation
RSM	Response Surface Methodology
SFC	Specific Fuel Consumption
SwRI	Southwest Research Institute
TOC	Total Operating Costs
TOFL	Takeoff Field Length
TOGW	Take-off Gross Weight
T/W	Thrust-to-Weight
U	Utilization
Vapp	Approach Speed
VLT	Very Large Transport
VT	Vertical Tail

1. Introduction

In recent years, airlines worldwide have experienced numerous financial difficulties. In fact, many feel that the need for long range business travel may be declining in the era of satellite communications, computer networking, and electronic mail. However, the 1997 Boeing Market Outlook forecasts that world air travel is expected to grow at a rate of 5.5% per year over the next decade, resulting in a 75% increase from current levels within a decade and increasing to 150% in two decades [1]. Economic analysts anticipate this predicted increase to be due to growth in the Asian-Pacific air transport market over the next twenty years [2,3].

This potential increase in traffic is expected to strain the existing infrastructure, creating a need for considerable expansion of existing airports or construction of new ones [4]. Neither of these expensive and politically impractical alternatives will answer the increased congestion problem, leaving only one viable option: development of a high capacity, long range aircraft, capable of meeting the increased travel demand while maximizing landing and takeoff slot utilization at existing airports [4]. In recent surveys [2,3], twelve airlines from Europe (including Lufthansa and Air France), the United States (e.g., United), and the Asian-Pacific region (including Cathay Pacific and JAL) saw the need for an airplane much larger than the B747-400, i.e., aircraft with capacities on the order of 600 to 1000 passengers. From these airline needs and air travel growth projections, a 1994 Airbus forecast showed a potential market for 1,000 high capacity aircraft [5], and later revised that figure to 1,400 in 1997 [6].

Even though these studies favorably show the need for a Very Large Transport (VLT) from an airline and airframe manufacturer point of view; the passenger's needs must also be considered. In fact, air travel is expected to move from the business market to the more price-sensitive tourist market in the coming decades where the tourist market is focused on increased comfort at reasonable ticket prices. In fact, comfort and affordability are key requirements from a passenger's point of view [7].

In order for a proposed VLT concept to be launched to full scale production, it must abide by existing FAR and EPA regulations, provide comparable safety and comfort to current long range subsonic fleets, remain compatible with existing airport infrastructures, and yield economic benefits to all interested parties: airframe manufacturer, airlines, airports, and passengers. Therefore, it is essential to maintain an affordable ticket fare for the passenger while retaining a reasonable return on investment (ROI) for the airlines and the airframe/engine manufacturers. The balance of these demands is captured by the metric of average required yield per revenue passenger mile ($/RPM).

Based on these requirements, the following system level goals were established for the development of a VLT concept:

- Define the problem by identifying relevant system level metrics, constraints, and geometric and economic variables;
- Determine if a technically feasible design space exists by quantifying impact of said problem definition on a conventional configuration;
- Qualify and quantify impact of technology metric "k" factors to create a technically feasible design space if a conventional concept does not meet performance constraints;
- Investigate specific technologies which can supply the needed benefit to shift to a feasibility space; and
- Assess the economic viability of the design space.

Based on Airbus' market studies [7], NASA Langley studies [8], and current long-range commercial transport data, a VLT mission profile would resemble that depicted in Figure 1.

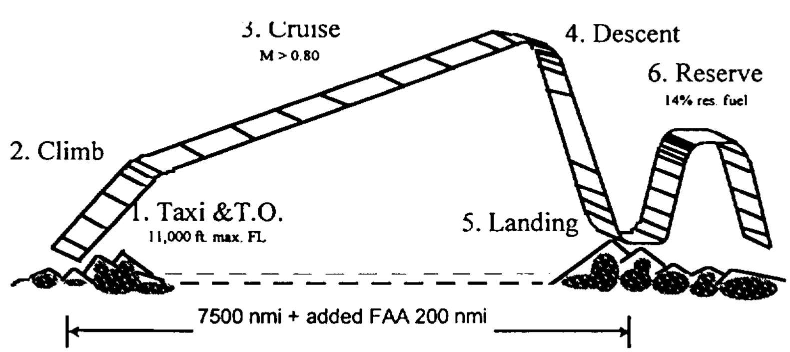
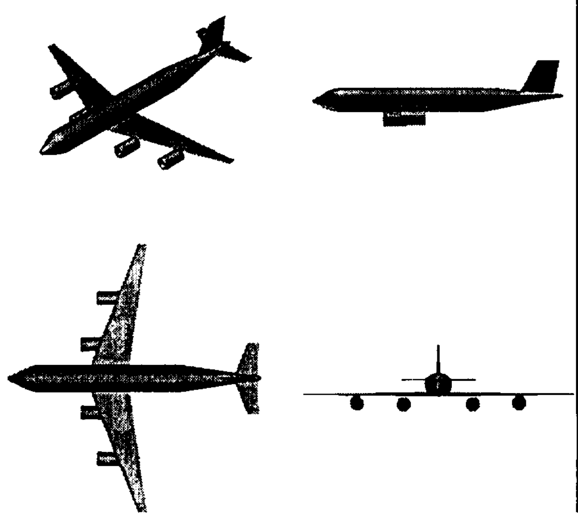


FIGURE 1: VLT MISSION PROFILE

Based on the economic viability study of VLT configurations in Reference [9], a tri-class 800 passenger configuration was selected as the vehicle of interest for this study. Figure 2 illustrates the basic geometric layout. The economic viability assessment of Ref. [9] was intended to identify the appropriate-sized vehicle for given markets, subject to economic uncertainty for fixed design parameters. Furthermore, the viability assessment of that study was based on the point design solutions obtained in Reference [8]. These point designs were subjected to economic uncertainty to quantify the economic viability for that point solution. In contrast, this study considers the design from a top level point of view. This shift in focus allows geometric and mission design parameters to enter the assessment in order to expand the original point design to a design space. This space must be explored for feasible designs which are then subjected to economic viability assessments so as to determine the most robust solutions which exist. These geometric parameters will be described later.



Parameter	Value
Fuselage Length (ft)	250.0
Wing Span (ft)	267.5
Wing Area (sq ft)	6815.0
T/W	0.24
TOFL (ft)	11006
LDFL (ft)	4848
Approach Speed (kts)	105.6
TOGW (lbs)	1044828
Fuel Required (lbs)	409750
No. Flight Crew	4
Range (nmi)	7500
Pax. Capacity	800
Cruise Mach no.	0.80

FIGURE 2: BASELINE VLT GEOMETRY

2. Methodology Background

2.1 Fast Probability Integration

Recent developments in modern aircraft design theory at the Aerospace Systems Design Laboratory (ASDL) at Georgia Tech, form the basis for the approach taken for this investigation. Aircraft design is inherently a multi-disciplinary, multi-attribute, and multi-constrained problem; methods such as response surfaces, genetic algorithms, and multidisciplinary optimization techniques have not been completely efficient or successful in these situations. An alternative method based on the Fast Probability Integration (FPI) technique, is proposed and applied to this investigation. This technique provides *valuable* information in an efficient manner so as to perform system tradeoffs in a more realistic fashion. A brief description of FPI is given below and the reader is referred to References [10, 11] for more information of the theory and application of FPI.

The FPI computer program [12], developed by researchers at the Southwest Research Institute (SwRI) for the NASA Lewis Research Center, is a probability analysis code based on the determination of a Most Probable Point (MPP); a concept analysis frequently used in structural reliability analysis. The MPP analysis utilizes a response function $Z(\mathbf{X})$ that is a function of several random variable distributions. Each point in the design space spanned by the $\mathbf{X}_i$'s has a specific probability of occurrence according to their joint probability distribution function. Thus, each point in the design space corresponds to one specific response value $Z(\mathbf{X})$ which has a given probability of occurrence.

In cost analysis and other disciplines involving random variables, it is often desirable to find the probability of achieving response values below a critical value of interest, z_0. This critical value can be used to form a limit-state function (LSF),

$$g(\mathbf{X}) = Z(\mathbf{X}) - z_0 \qquad (1)$$

where values of $g(\mathbf{X}) \geq 0$ are undesirable. The MPP analysis calculates the cumulative probability of all points that yield $g(\mathbf{X}) \leq 0$ for the given z_0. Since the LSF "cuts off" a section of the joint probability distribution, a point with maximal probability of occurrence can be identified on that LSF. This point is called the Most Probable Point. It is found most conveniently in a transformed space in which all random variables are normally distributed as shown in Figure 3. Once the MPP for a given probability is identified, the process can be repeated for several z_0 values, mapping each probability over the normalized distribution space to get a cumulative probability distribution (CDF). This CDF for Z(**X**) can than be differentiated to obtain the probability density function of the response.

The FPI code offers several very efficient and accurate techniques for approximating the CDFs which eliminate the need for an expensive Monte Carlo Simulation. An additional advantage of FPI is the fact that it wraps around an analysis code, eliminating the need for a metamodel, such as Response Surface Equations (RSE). The elimination of RSEs allows for the inclusion of more variables and higher accuracy since the actual analysis code is utilized in lieu of a quadratic polynomial approximation.

This study utilized the Advance Mean Value + (AMV+) analysis mode in FPI for all design space assessments. AMV+ was chosen as the appropriate FPI technique after a comparison of methods was performed. AMV+ most closely approximated a Monte Carlo generated CDF of the actual analysis tools.

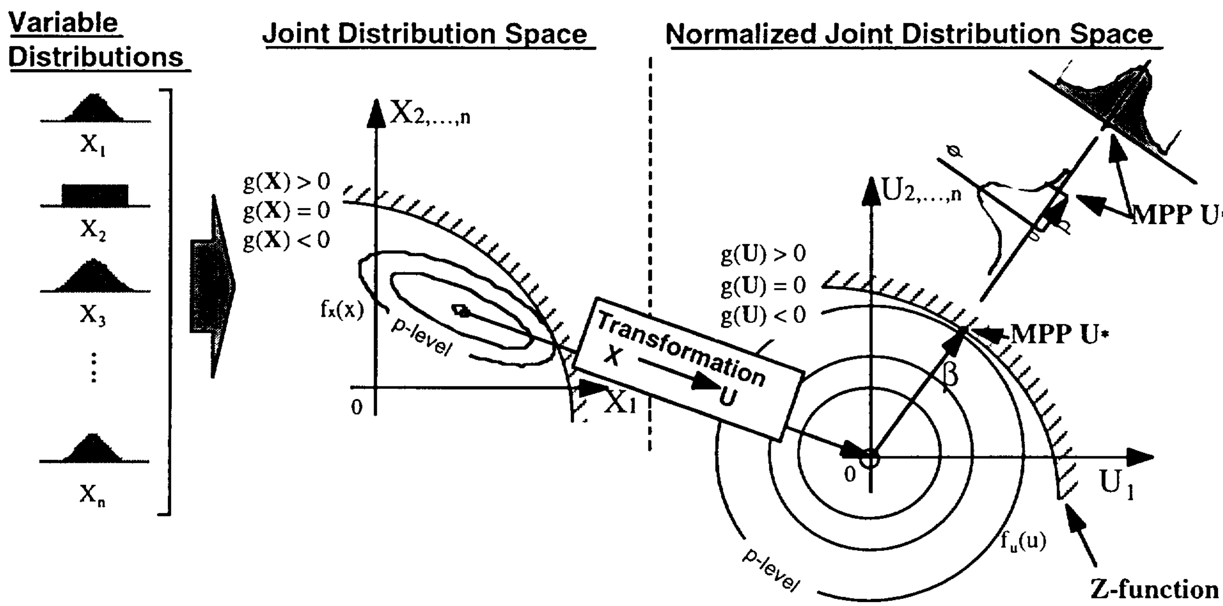


FIGURE 3: FPI DISTRIBUTION TRANSFORMATION

2.2 FLOPS/ALCCA

All aircraft sizing and analysis tasks for this study utilized the Flight Optimization System, FLOPS, a multidisciplinary system of computer programs used for the conceptual and preliminary design and analysis of aircraft configurations [13]. This tool was developed by the NASA Langley Research Center. FLOPS was linked to an Aircraft Life Cycle Cost Analysis, ALCCA, program used for the prediction of all life-cycle costs associated with commercial aircraft and was developed by NASA Ames and further enhanced by ASDL [14]. The direct link of FLOPS and ALCCA provided the capability to create a conceptual aircraft design with immediate evaluation of life-cycle cost elements.

FPI wrapped around FLOPS/ALCCA and controlled the variation of inputs in accordance with the assigned probability distributions. The code was executed, pertinent output tabulated, and the next combination of input settings prepared to repeat the process. This continues until the CDF for the specified responses at given p-levels is established.

3. Approach

The FPI technique described above was applied to a VLT design problem via the methodology depicted in Figure 4. To summarize, the technical feasibility and economic viability of a VLT concept was assessed in six primary steps:

1. Define the problem
2. Determine system feasibility
3. Determine economic viability
4. Evaluate the probability of obtaining a feasible and viable design space
5. Infuse new technologies if these probabilities prove unsatisfactory (repeat 1-4)
6. Examine design solutions and robustness

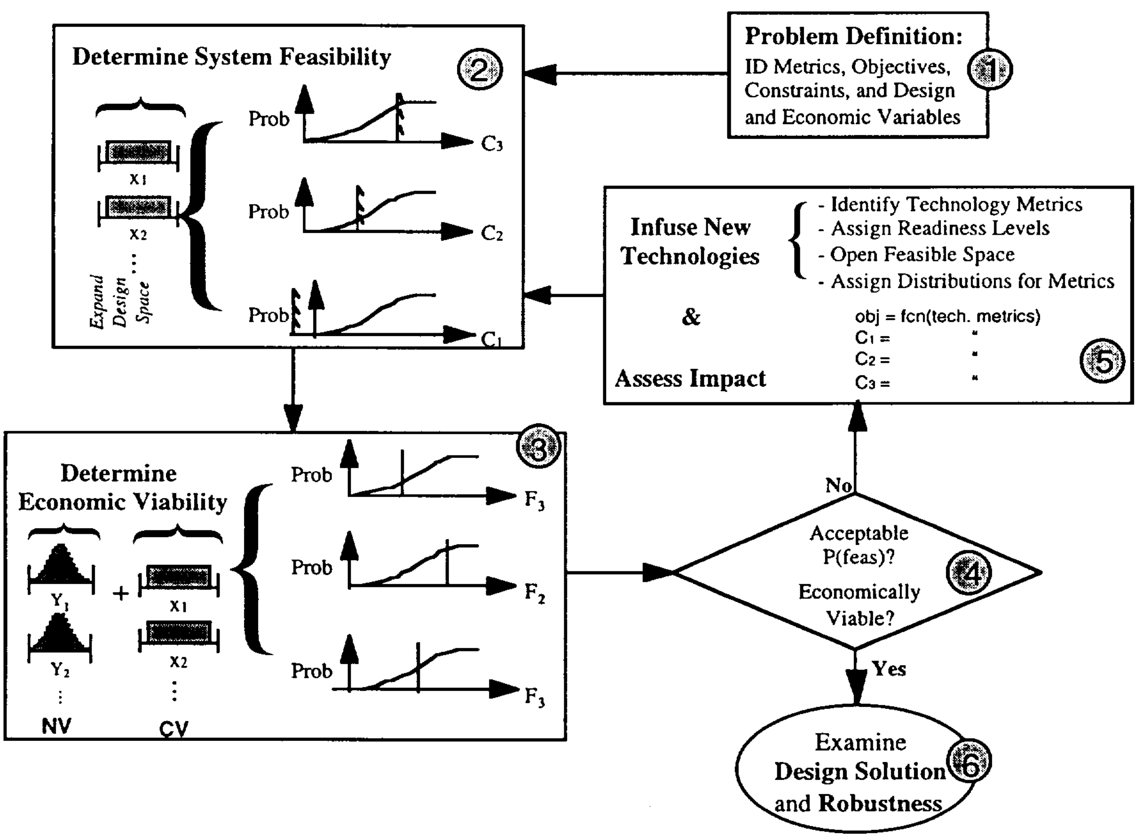


FIGURE 4: OVERALL METHODOLOGY FLOW

3.1 Define The Problem

A primary aspiration of a VLT is to be competitive with existing large capacity transport aircraft with respect to \$/RPM, acquisition price, and total operating cost (TOC) per trip. Additional objectives arise from the need to maintain comparative performance characteristics (approach and cruise speeds) and remain compatible with existing airport infrastructures (constrained takeoff gross weights and takeoff and landing field lengths). Hence, this problem requires the definition of objectives or metrics which capture the needs of the airframe manufacturer, airlines, airports, and passengers. "Metrics" are figures of merit that characterizes various disciplines involved in a system's development. The metrics/objectives for this study are primarily economic or performance based and are: \$/RPM, TOC, acquisition price (Acq \$), Research, Development, Testing, and Evaluation (RDTE), takeoff gross weight (TOGW), takeoff field length (TOFL), approach speed (V_{app}), and landing field length (LDGFL).

The target and constraint values were identified for each objective as established from Reference [2, 8, and 9], current airport infrastructures, and FAA regulations. The constraints were the "rigid" limits placed on the performance and economic objectives of the vehicle, while targets were simply goals whereby achievement is strongly desirable. These values are summarized in Table I.

TABLE I: OBJECTIVES AND TARGETS/CONSTRAINTS

Objective	Target	Constraint
Performance		
Takeoff Gross Weight (TOGW)	*minimize*	< 1 million lbs
Takeoff Field Length (TOFL)	*minimize*	< 11,000 ft
Landing Field Length (LDGFL)	*minimize*	< 11,000 ft
Approach Speed (V_{app})	*minimize*	< 150 knots
Economic		
Acquisition Price (Acq \$)	*minimize*	*N/A*
TOC per trip	*minimize*	*N/A*
RDTE	*minimize*	*N/A*
\$/RPM	≈ \$0.085	\$0.115

The performance metrics were defined in terms of key design variables for specified ranges. These design variables are often referred to as "control" factors, that is, the variables in a design problem within the designer's control. Examples include wing aspect ratio (AR), maximum thickness-to-chord (t/c) ratios, quarter-chord sweeps, horizontal tail (HT) and vertical tail (VT) areas, and thrust-to-weight ratio (T/W). The variables identified as pertinent to the design were based on an aerodynamic optimization procedure performed in Reference [15] and a system level study performed in Reference [16] and are summarized in Table II.

TABLE II: DESIGN VARIABLES

Variable	Minimum	Maximum
Cruise Mach number	0.78	0.83
HT AR	3.6	4.2
HT area	1225 ft^2	1400 ft^2
HT sweep	18°	40°
T/W	0.24	0.28
VT AR	1.15	1.40
VT area	900 ft^2	1400 ft^2
VT sweep	24°	50°
Wing AR	8.	11.
Wing ref. area	5800 ft^2	6800 ft^2
Wing sweep	22°	40°
Wing t/c	0.09	0.11

The economic metrics are primarily functions of "noise" factors, or variables beyond the designer's grasp that affect the fulfillment of the system objectives. For example, the cost of fuel will directly affect the operating costs of an aircraft, yet the designer cannot "design for" a given fuel cost. The economic variables of relevance are based on the results of Reference [9] and summarized in Table III. The production quantity was increased from 300-800 production units to a range of 650-1150 based on recent projections by Boeing [1] and Airbus [5,6]. All remaining noise variables were fixed to their most likely values. These fixed values were the assumptions of the analysis in this study, as summarized in Table IV.

TABLE III: ECONOMIC VARIABLES

Variable	Minimum	Maximum
Airline ROI	5%	15%
Economic range	3000 nmi	7000 nmi
Fuel cost	$0.54/gal.	$0.88/gal.
Manufacturer's ROI	10%	20%
Mfg. learning curve	74%	82%
Passenger load factor	45%	85%
Production quantity	650	1150
Utilization	4500 hrs/yr	5500 hrs/yr

TABLE IV: ECONOMIC ANALYSIS ASSUMPTIONS

Parameter	Value
Dollar Year	1992
Down Payment	20%
Economic. Life (years)	20
Eng. Labor Rate ($/hr)	89.68
Engine Learning Curve	100%
Hull Ins. (% of acq. price)	35
Income Tax Rate	34%
Inflation Rate	6%
Maintenance Labor Rate ($/hr)	19.5
Production Year	2005
Residual Value (% of acq. price)	10
Tooling Labor Rate ($/hr)	54.86

3.2 Feasibility And Viability

As stated previously, the FPI technique provides a CDF for the defined objectives based on the variables listed in Table II and Table III. The CDF can be compared to the appropriate target and the probability of a feasible or viable design space can be assessed. An example of the feasibility assessment is shown in Figure 5. The probability of success is determined by placing the objective target on the CDF and reading the corresponding probability value. Any probability of achieving a solution is favorable since it represents the outcome of design variables. Yet, the decision maker still strives for alternatives which maximize the feasible and viable design space.

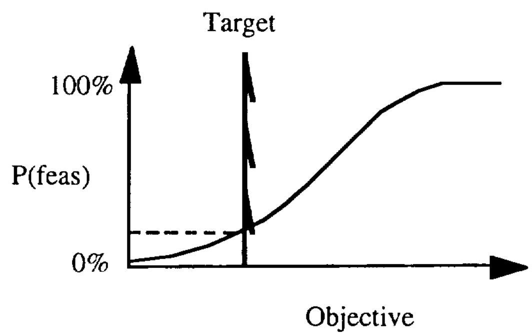


FIGURE 5: FEASIBILITY EVALUATION

3.2.1 Determine Technical Feasibility

Technical feasibility is a measure of the system's ability to meet the imposed performance targets and to satisfy all constraints. Referring to Table I, all four performance objectives are constrained, specifically by aviation regulations and airport compatibility. Therefore, in order to be successful, a VLT must satisfy each constraint with a sufficiently high probability value; exact value is determined by the designer or decision maker. In other words, the larger the magnitude of the probability, the larger the feasible design space, i.e. more alternatives, in which robust solutions may exist.

For the technical feasibility assessment, only the stated control variables were allowed to vary in the manner described previously. These variables were set up in FPI to vary between the stated minimum and maximum values using uniform distributions. This allows all possible values within the ranges specified to become equally likely. The result is a CDF (similar to Figure 5) for the different performance metrics and this allows for quick assessment of technical feasibility.

3.2.2 Determine Economic Viability

Economic viability is a measure of the system's ability to achieve specified cost and profitability goals as well as satisfy any constraints imposed. From Table I, only $/RPM is constrained to under $0.115. As stated previously, the Boeing 747-400 achieved this value in Reference [9]. Hence, for commercial success, a VLT must attain lower values ($0.085) in order to satisfy the needs for greater profitability with lower fare premiums. It is thus imperative that a VLT satisfy this constraint with at least a 70% probability. The remaining objectives are limited by aspirations, rather than constraints. In other words, the specific values for these last three objectives (acquisition price, RDTE, and TOC per trip) need not meet any specific value, so long as the given aircraft does not violate the $/RPM constraint.

For the economic viability assessment, control and noise variables were set in FPI to vary between the stated minimum and maximum values using uniform and normal distributions, respectively. Thus, FPI generated CDF data for the four economic objectives which is valid for the design space under consideration. The viability assessment is performed in the same manner as feasibility with the CDF target.

3.3 Evaluate The Probability Of Feasibility And Viability

The evaluation of feasibility and viability of a VLT is based on the value of the probability of a given objective for the specified target value. For example, if an objective has an 80% chance of achieving the target, the decision-maker may assume that this objective is no longer a constraint and does not warrant further investigation. Yet, a low probability value (or small chance), of achieving a solution that satisfies the constraints implies that a means of improvement must be identified; perhaps infusion of new technology. This process of evaluation must be performed for each objective and constraint.

3.4 New Technology Infusion

The infusion of new technologies can be considered in the aircraft design process when the feasibility and economic viability probability space for a given vehicle concept are not within acceptable limits to the decision-makers. The need for the infusion of a technology is required when the manipulation of the variable ranges has been exhausted, optimization is ineffective, constraints are relaxed to a minimum, and the maximum performance attainable from a given level of technology is achieved. The maximum level of a given technology is essentially the natural limit of the benefit, displayed in Figure 6. This implies that the maturation variation with time remains constant. When this limit is reached, there is *no other alternative* but to infuse a new technology.

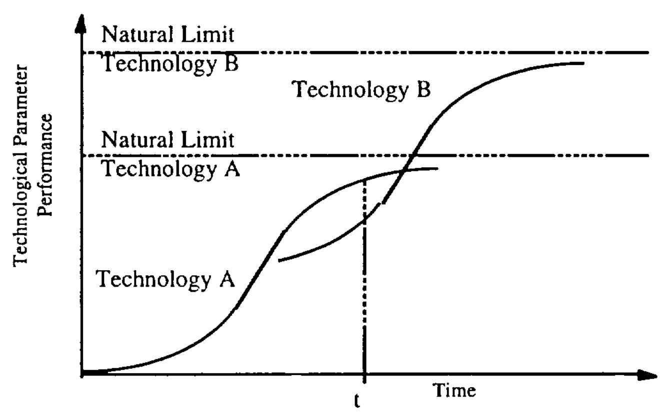


FIGURE 6: NEED FOR NEW TECHNOLOGY INFUSION [17]

3.5 Technology Impact Assessment

The infusion of new technologies for a given configuration must be considered when all other alternatives (optimization, opening design space, etc.) have been explored. Unfortunately, advanced technologies are difficult to assess. Sizing/synthesis tools are typically based on regressed historical data which limits or removes the applicability to exotic concepts or technologies. Furthermore, higher fidelity tools, such as finite element methods and computational fluid dynamics can not always capture the physics associated with a new technology nor do these tools allow for rapid parametric assessments of a design space.

However, the impact of a technology can be qualitatively assessed through the use of technology metric "k" factors. These "k" factors modify technical metrics, such as specific fuel consumption (SFC), cruise drag, hence Lift-to-Drag ratio (L/D), component weights, and RDTE costs that result from some analysis or sizing tool. The modification is essentially a change in the technical metric, either enhancement or degradation. In effect, the "k" factors simulate the discontinuity in benefits or penalties associated with the addition of a new technology.

The impact of "k" factors on the system objectives and constraints can be assessed qualitatively through a linear or higher order sensitivity analysis depending on the level of detailed desired. The analysis can be performed with the prediction profile feature of the JMP statistical package [18], such as the example depicted in Figure 7. The metric in this example is L/D. One can assume that the L/D can be improved by some *generic* technique, say laminar flow control. This technology supplies, not only benefit, but a penalty or degradation in the system associated with that technology. For laminar flow control, this penalty comes through increased SFC and reduced utilization. The SFC is increased due to engine bleeding and power extraction needed for the suction effect over wing. This degradation is shown in Figure 7. As the "k" factor increases towards "1", the benefit of improved L/D increases, yet, the penalty of the increasing SFC, towards "+1", reduces the benefits. Utilization is also affected through increased maintenance efforts, increased component weights due to required ducting, and higher maintenance man hours per flight hour.

$$\mathrm{OBJ} = \left[k_{m_1}(\mathrm{metric}_1) + k_{m_2}(\mathrm{metric}_2) + \ldots\right] + \left[k_{p_1}(\mathrm{penalty}_1) + k_{p_2}(\mathrm{penalty}_2) + \ldots\right]$$

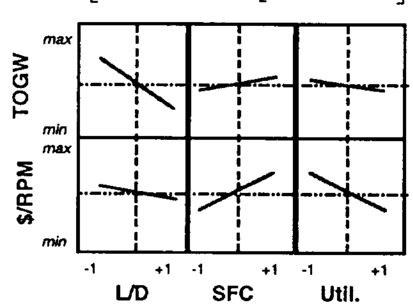


FIGURE 7: EXAMPLE "K" FACTOR PREDICTION PROFILE

However, if a "k" factor for a given technological metric is shown to improve the system objectives and constraints with minimal penalties, that technology impact can be identified as worthy of further investigation. An actual technology must be identified which can provide the "k" factor projections. This method is essentially forecasting the impact of a technology. This technique provides a very efficient means of identifying design alternatives around concept "show-stoppers". As a result, technologies capable of counteracting the show-stoppers aid in the correct allocation of resources for further research and development of the project.

3.6 Examine Design Solutions and Robustness

Once technological metrics are identified which can provide the given performance improvement, the FPI technique can be applied again to assess improvements in feasibility or viability. This is done by comparing the CDF of the conventional baseline to the enhanced configuration with respect to the target value (Figure 8). This method can be applied to each objective and constraint which did not satisfy the specified targets within an acceptable limit so as to yield a first estimate to the benefit of a given technology.

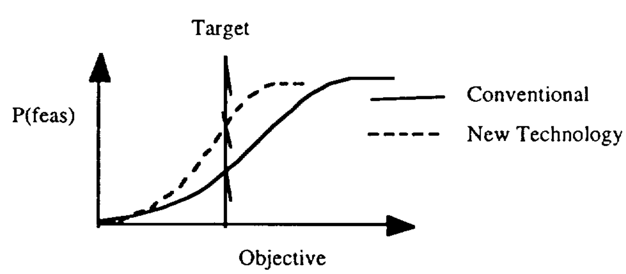


FIGURE 8: NEW TECHNOLOGY IMPROVEMENT

Once the CDFs for the objectives are obtained, the feasible and viable design space can be evaluated. Overall improvements may or may not exist requiring quantification of the extent to which the system satisfies or violates objectives. The decision maker may then elect to continue allocation of resources for further research or terminate the efforts. If the probability levels for a feasible or viable space are on the order of 20-70%, the risk associated with technologies, uncertainty, and scheduling must be addressed.

4. Results

The "baseline" VLT aircraft used as the starting point for this study was developed in References [8, 9]. As stated previously, those studies *only* considered the benefit associated with the addition of new technologies for a fixed point design. This study extends the analysis of this aircraft into a probabilistic exercise to assess the feasibility and viability of a VLT design space.

4.1 Feasibility and Viability Assessment

Executing the first three steps of the approach, the conventional baseline aircraft failed to demonstrate an acceptable level of technical feasibility. If any of the objectives are not satisfied, then the solution is considered to be unattainable, specifically the TOGW did not satisfy the one million pound constraint with any designs. This result is seen in Figure 9, where the CDF curve for TOGW lies completely on the unfeasible side of the constraint (represented by the vertical line). Furthermore, less than 21% of the design space could achieve TOFL under 11,000 ft (Figure 10). On the contrary, the landing approach speed (Figure 11) and landing field length (Figure 12) objective constraints were consistently satisfied (i.e., 100% feasible design space) due to the high wing loading values achieved with the selected design parameter ranges. Even though these two performance metrics constraints were achieved, the design space is not feasible since the TOGW constraint was not satisfied.

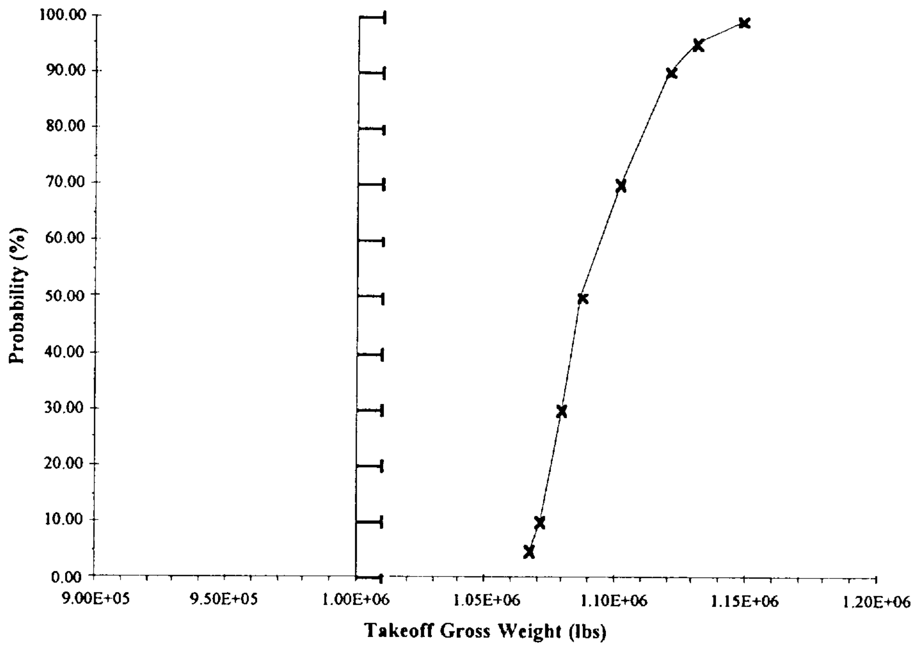


FIGURE 9: TECHNICAL FEASIBILITY ASSESSMENT (TOGW)

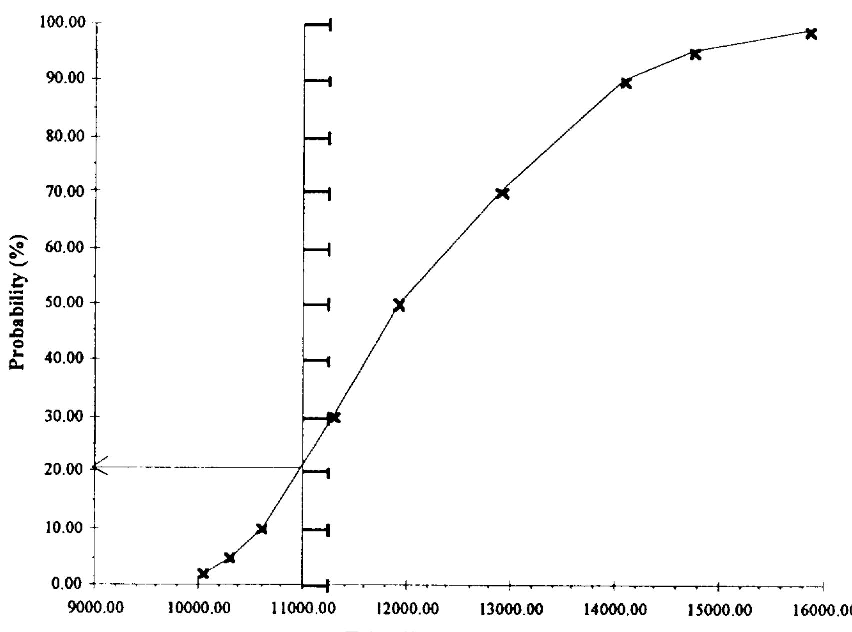


FIGURE 10: TECHNICAL FEASIBILITY ASSESSMENT (TOFL)

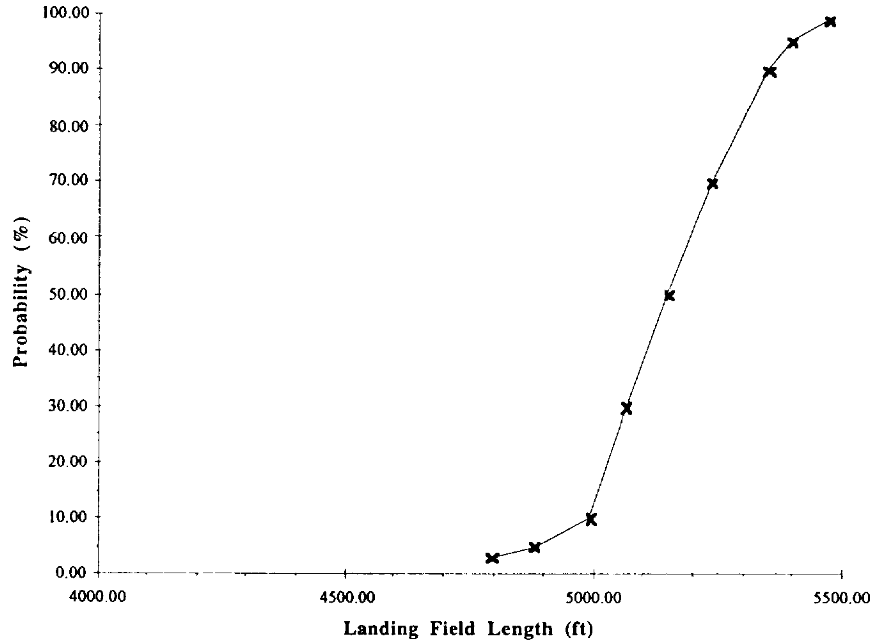


FIGURE 11: TECHNICAL FEASIBILITY ASSESSMENT (LDGFL)

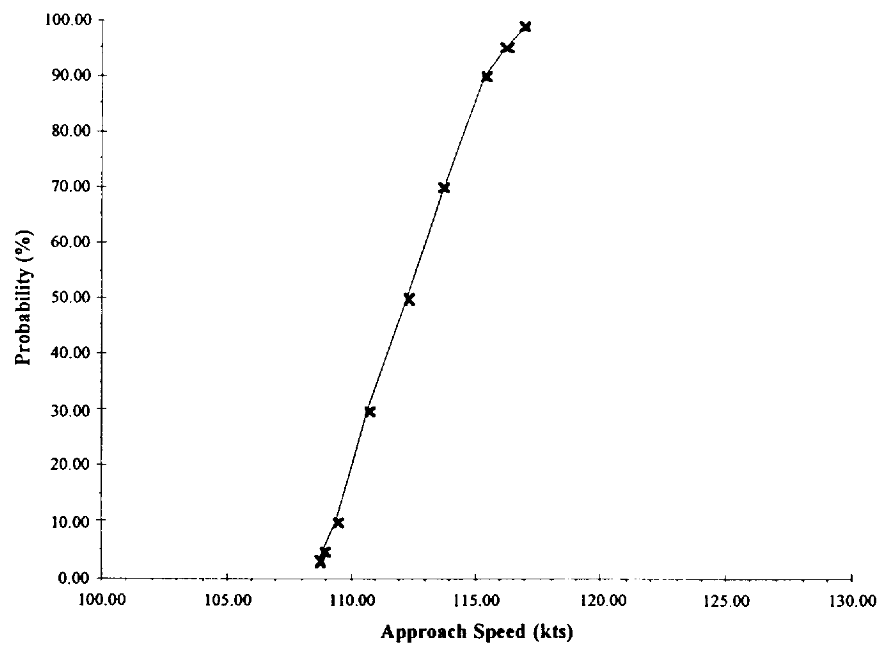


FIGURE 12: TECHNICAL FEASIBILITY ASSESSMENT (VAPP)

Similarly, the baseline aircraft did not achieve the desired 70% probability for economic viability. The conventional VLT could satisfy the $/RPM goal with a reasonable probability as illustrated in Figure 13. While 66% of the VLT design space is viable, the space is not technically feasible due to the violation of TOGW. The results obtained for the remaining economic objectives in this study are depicted in Figure 14 through Figure 16. The targets for these objectives were simply minimization. Since the B747-400 is the only high capacity aircraft in commercial use, rigid constraints could not be established. A possible target of a 30% increase for the remaining economic metrics could be assumed. The B747-400 acquisition price is approximately $150-174 million [1] with a TOC per trip of $157,000 and the RDTE on the order of $15 billion. Hence, if a 30% increase is assumed, the economic targets would become $195-$226 million for acquisition price, $204,000 for TOC per trip, and $19.5 billion for RDTE. An optimistic acquisition price target of $195 million will be used.

Based on the assumed targets stated above, 22% of the VLT design space could achieve the assumed acquisition price target of $195 million (Figure 14). None of the designs could meet the RDTE goal of $19.5 million as shown in Figure 15. The RDTE goal could not be met since the calculation of RDTE is primarily weight based and the VLT design space TOGW values are greater than one million pounds, the RDTE value will also be high. The TOC target was achieved by 12% of the designs as shown in Figure 16.

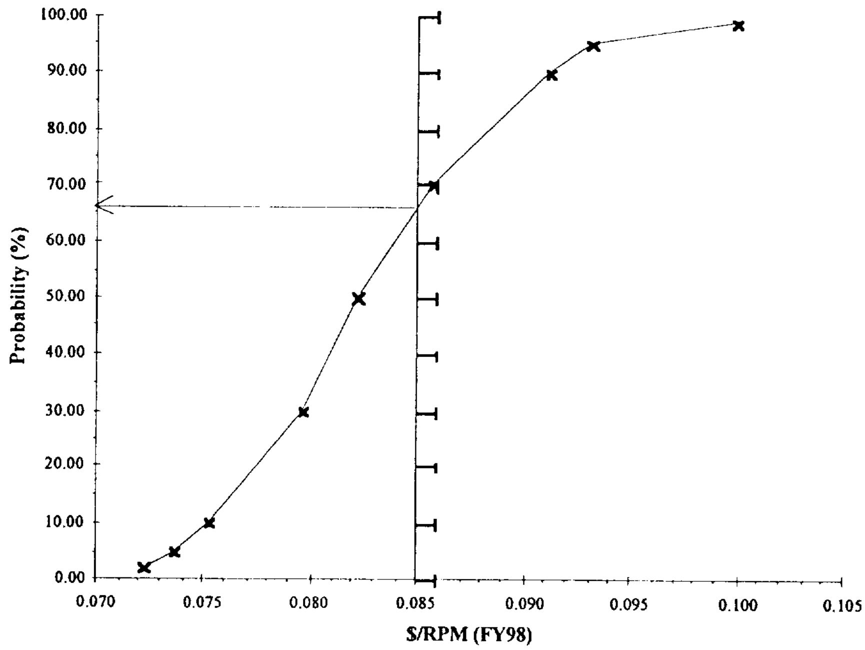


FIGURE 13: ECONOMIC VIABILITY ASSESSMENT ($/RPM)

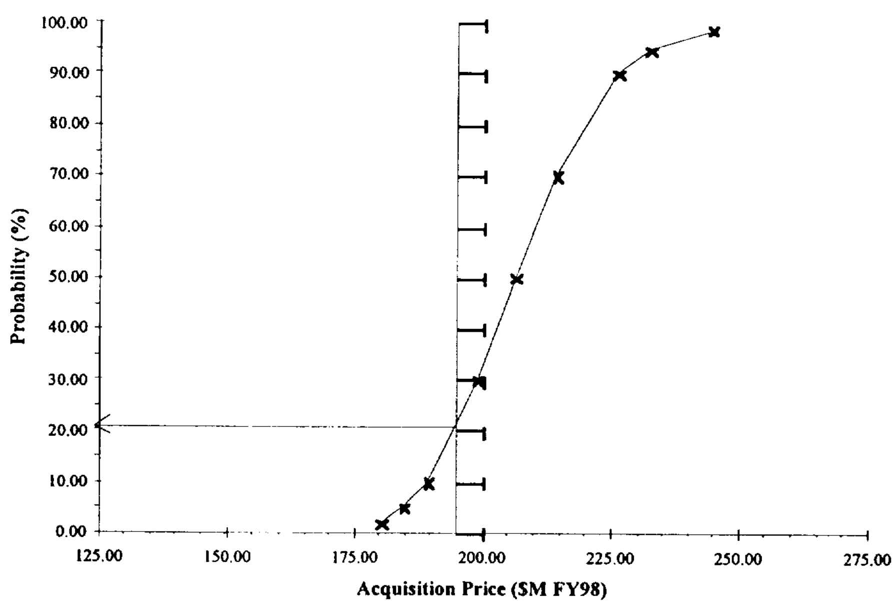


FIGURE 14: ECONOMIC VIABILITY ASSESSMENT (ACQ $)

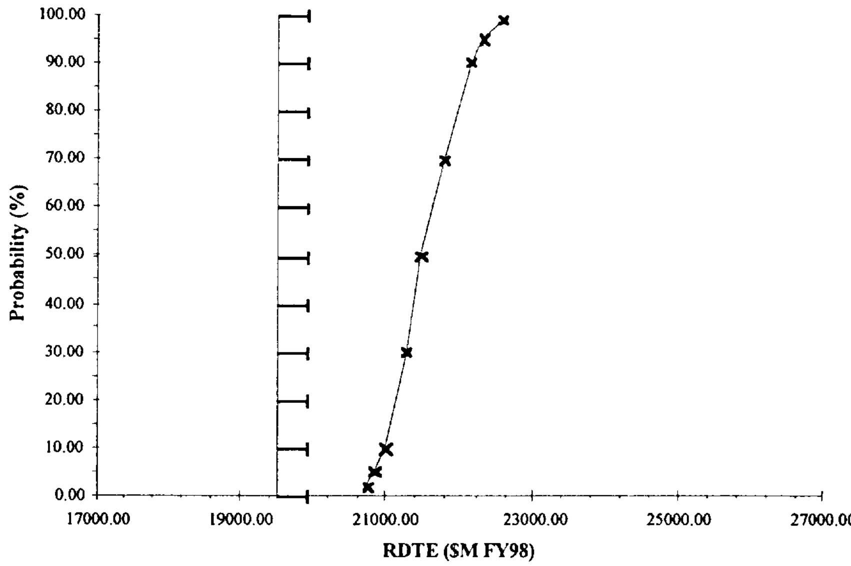


FIGURE 15: ECONOMIC VIABILITY ASSESSMENT (RDTE)

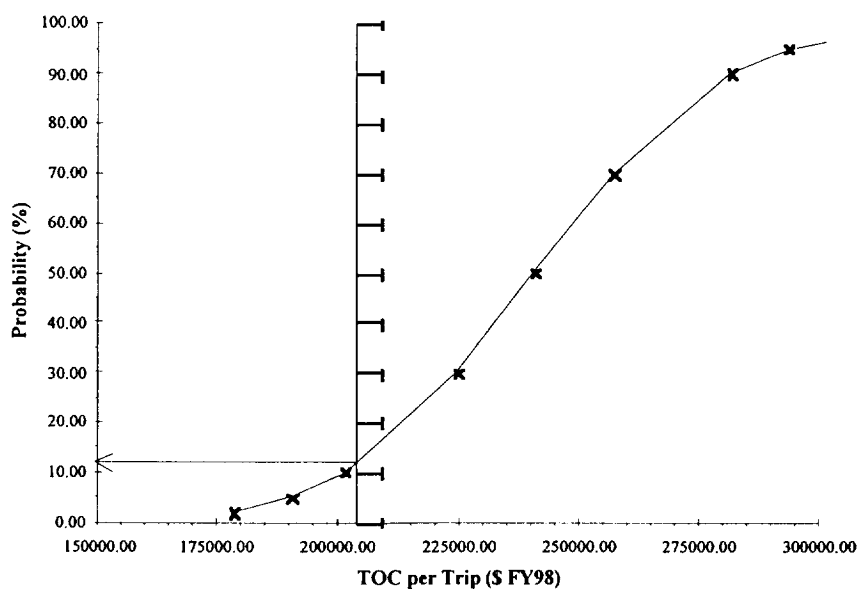


FIGURE 16: ECONOMIC VIABILITY ASSESSMENT (TOC)

4.2 Technology Infusion

The baseline VLT resulted in technically unfeasible solutions in the initial investigation. Considering that the control parameter ranges were based on maximizing the probability of feasible design, a VLT *must* be infused with new technologies. As described previously, a guideline to the technologies worth investigating can be facilitated through the qualitative manipulation of the technology metric "k" factors. Four primary technological benefits were considered: SFC reduction, drag reduction and hence L/D increases, component weight reduction, and advanced conceptual design processes in the RDTE phases. The component weight reduction was assumed only for the wing, although other components can be considered.

The technologies associated with each "k" factor were further assumed to penalize other systems or support efforts. The assumed benefits of a technology and associated penalties are shown in Table V and should remain as general as possible. Values greater than 0% for SFC, drag, wing weight, and RDTE are assumed to be penalties to the system from the benefit of another metric. Furthermore, the utilization of the vehicle was allowed to vary to show the impact that a new technology would have on the elements of utilization: mean time to repair, mean time between failures, operational availability, block time, turn around time, scheduling, curfews, etc. This generality will allow for any technological infusion as long as appropriate values for the factors are justified.

TABLE V: TECHNOLOGY "K" FACTORS AND PENALTIES

"k" factors	Impact range
Drag (k_Drag)	-10 to 5%
RDTE (k_RDTE)	-10% to 10%
SFC (k_SFC)	-5 to 5%
Utilization (k_U)	4000 to 5500 hr/yr
Wing weight (k_wing)	-30 to 5%

In a realistic setting, the above factors are dependent upon each other if the configuration geometric parameters are allowed to vary. Yet, this dependency can be removed if the configuration geometry is fixed. Hence, a two level screening test was performed to identify the design variable settings which would minimize the objectives and thus become the fixed configuration for the application of the metric "k" factors with FPI. All control and noise variables were allowed to vary between the minimum and maximum values stated previously. The JMP statistical package was utilized to generate an effects screening prediction profile for all objectives as functions of the control and noise variables. The control factors which resulted in minimization of all objectives are summarized in Table VI. The point design metrics solution for these parameters are listed in Table VII.

The design parameters below were fixed along with the midpoint values of all economic parameters and the FPI technique applied again to estimate the impact of the addition of new technologies. The resulting CDFs for technical feasibility are depicted in Figure 17 through Figure 20. New technology infusion has created a small feasible region of 22% for the TOGW, Figure 17, as compared to 0% for the conventional configuration. The TOFL was increased from 21% to 96% in Figure 18. And, both the LDGFL and V_{app} CDFs were improved as depicted in Figure 19 and Figure 20, respectively. Al figures show the "optimal" solution.

TABLE VI: VLT SCREENING FOR "OPTIMAL" SOLUTION

Parameter	Value
Cruise Mach number	0.83
HT AR	3.9
HT area	1225 ft^2
HT sweep	18°
T/W	0.26
VT AR	1.15
VT area	900 ft^2
VT sweep	37°
Wing AR	11
Wing ref. area	6800 ft^2
Wing sweep	22°
Wing t/c	0.11

TABLE VII: OPTIMAL DESIGN METRICS

Objective		Value
Performance		
	TOGW	1,094,542 lbs
	TOFL	10,493 ft
	LDGFL	4,965 ft
	V_{app}	108.2 knots
Economic		
	Acq $	$M 210.2
	TOC	238,237
	RDTE	$M 22,069
	$/RPM	$0.081522

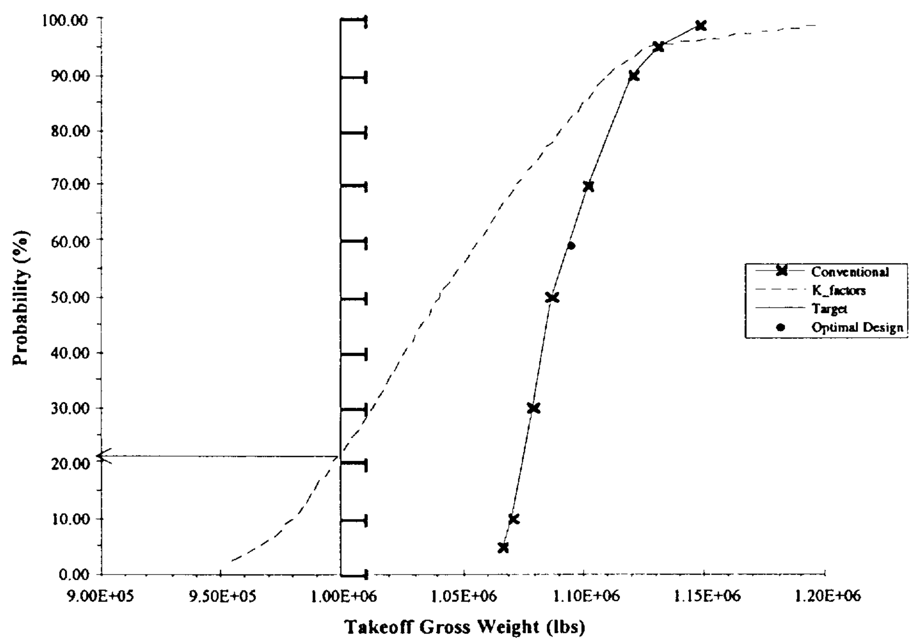


FIGURE 17: TOGW FEASIBILITY WITH "K" FACTORS

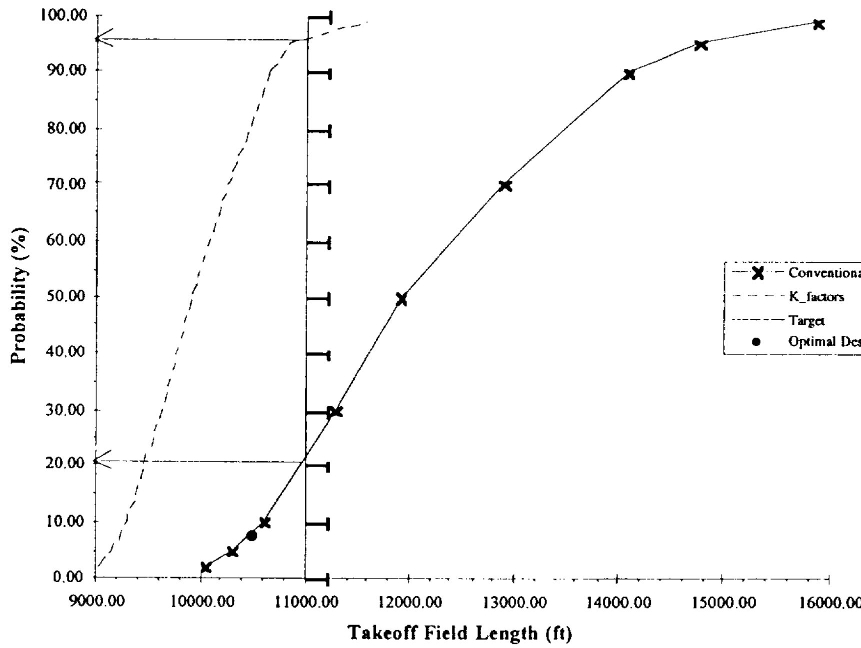


FIGURE 18: TOFL FEASIBILITY WITH "K" FACTORS

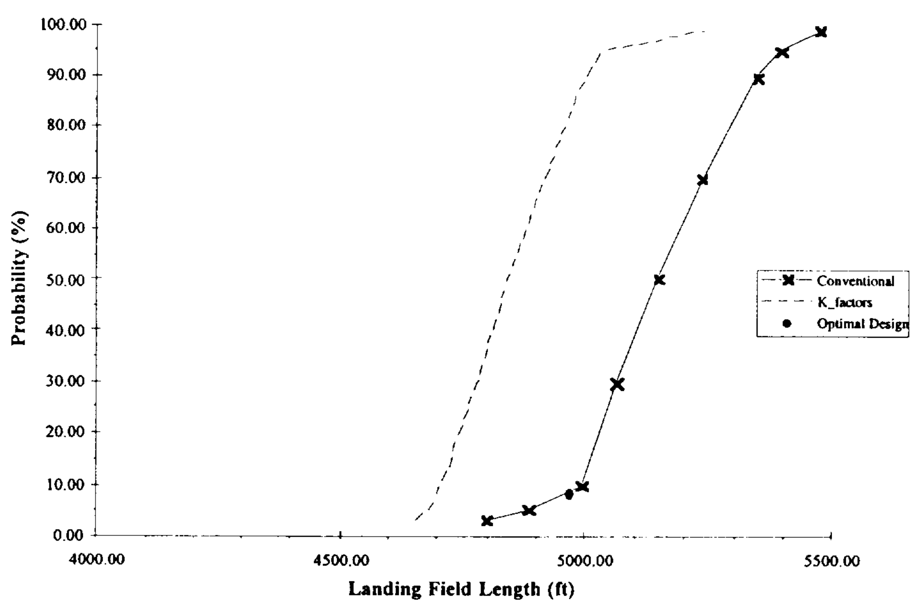


FIGURE 19: LDGFL FEASIBILITY WITH "K" FACTORS

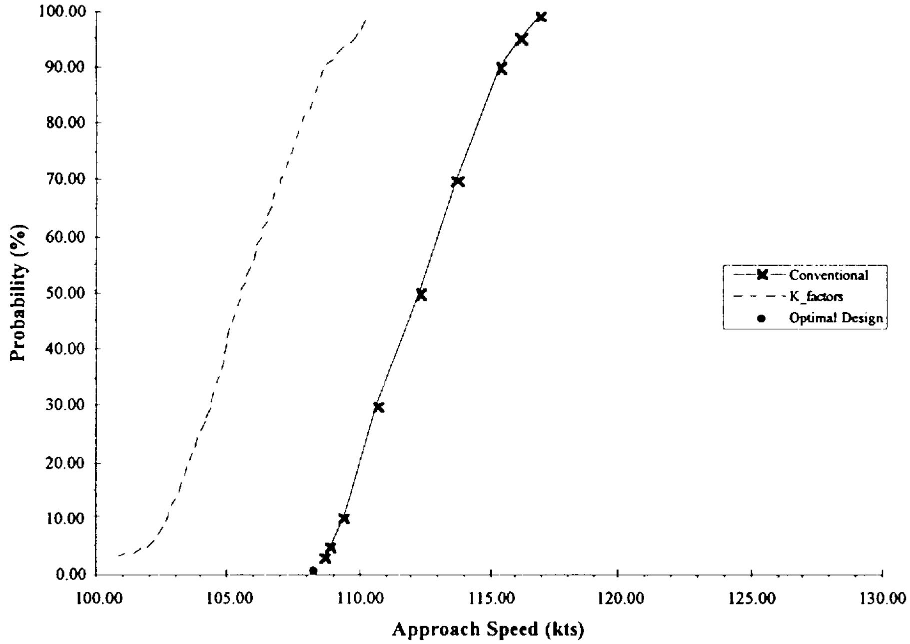


FIGURE 20: VAPP FEASIBILITY WITH "K" FACTORS

The impact of the “k” factors on the economic metrics is depicted in Figure 21 through Figure 24. The $/RPM was increased from 66% for the conventional configurations to 94% with technologies as shown in Figure 21. Furthermore, the acquisition price probability increased from 22% to 25% (Figure 22) and the RDTE from 0% to 26% (Figure 23). The only negative impact of new technologies on the viability was on the TOC which was reduced to 0%. Yet, the CDF was shifted more towards the target as shown in Figure 24.

The addition of new technologies to a conventional VLT design space has created feasible designs and increased the probability of achieving specified economic goals. Yet, it is unclear as to which technology “k” factor metric had the most impact on achieving a feasible space. Hence, further investigation of the “k” factors is needed.

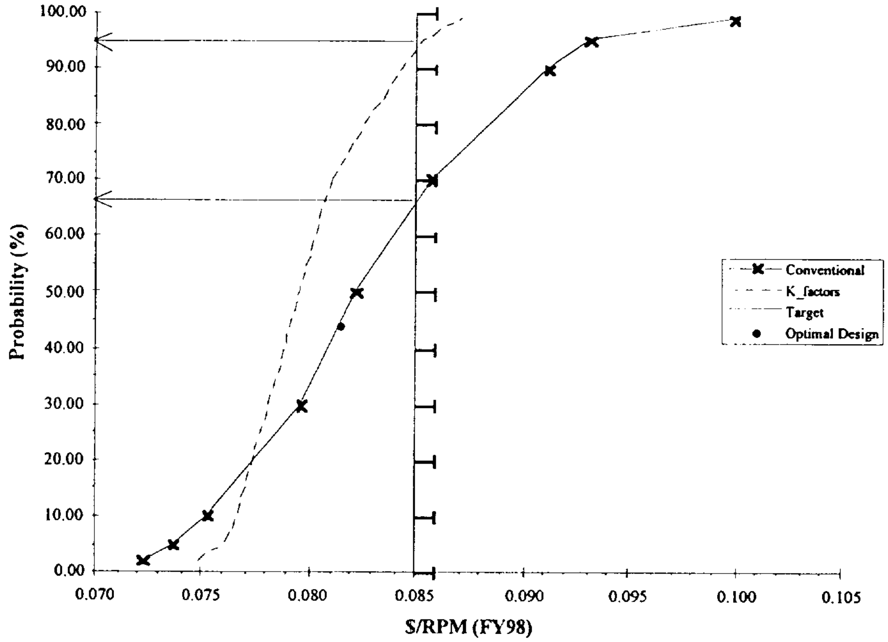


FIGURE 21: $/RPM VIABILITY WITH "K" FACTORS

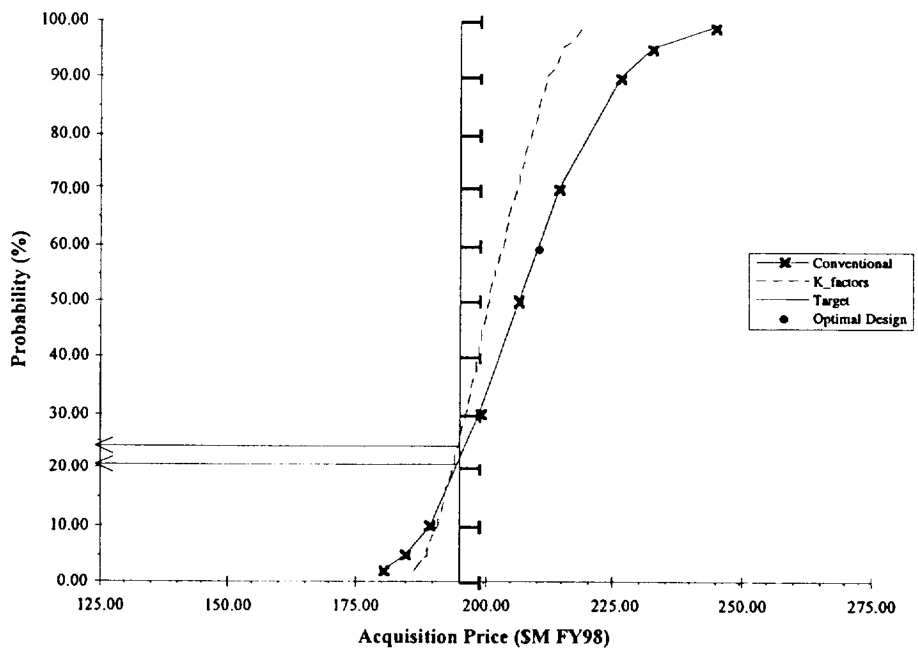


FIGURE 22: ACQ PRICE VIABILITY WITH "K" FACTORS

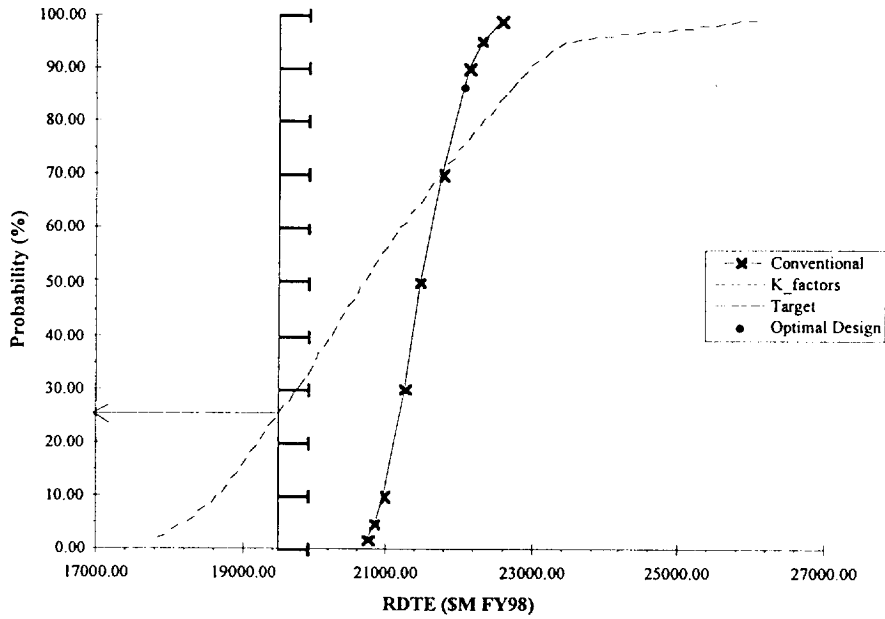


FIGURE 23: RDTE VIABILITY WITH "K" FACTORS

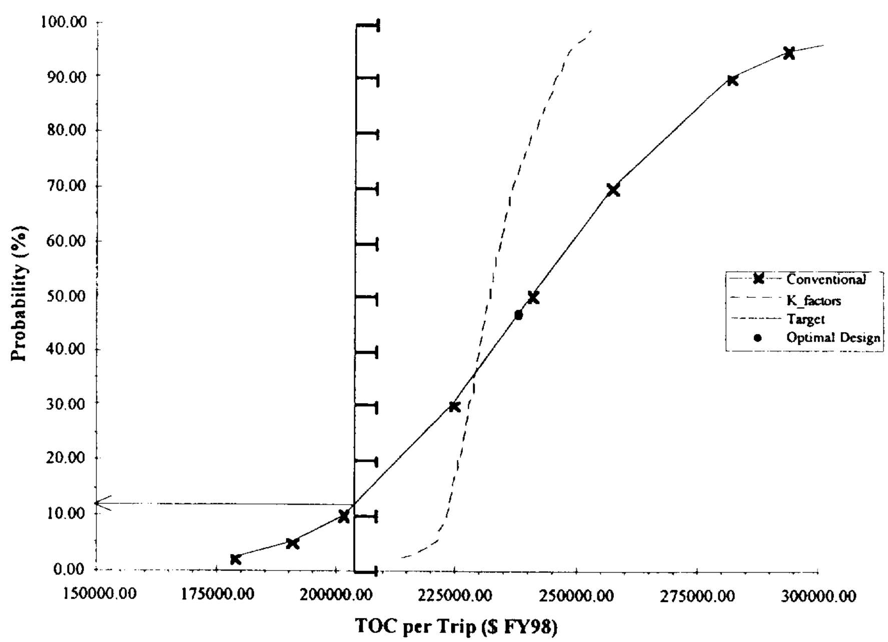


FIGURE 24: TOC VIABILITY WITH "K" FACTORS

To quantify the impact of individual "k" factors, a Box-Behnken Design of Experiments (DoE) was performed using the "k" factors with the addition of thrust-to-weight (T/W) ratio and wing area (Sref) which allowed for scaling of the vehicle. This technique is described in References [19, 20, and 21]. An effects screening test was performed with a quadratic model to quantitatively assess the impact of the individual "k" factors. The results from the DoE were analyzed with the JMP statistical package and a prediction profile was generated to quantify the effect of each parameter [18]. The prediction profile, shown in Figure 25, is evaluated based on the magnitude and direction of the slope, where the "-1" and "1" values shown above the "k" factors are normalized values with respect to the ranges identified in Table V. The larger the slope, the greater the influence of the given parameter. If a parameter, listed on the abscissa, does not contribute significantly to the response listed on the left, the slope is approximately zero. The sign of the slope, either positive or negative, depicts the direction of influence of the parameter on the response. For example, the increasing use of composites on the wing (i.e., towards "-1") increases the acquisition price due to the positive slope.

As can be seen above, the reduction of a technology "k" factor results in the decrease of a performance or economic metric. Whereas, an increase in utilization reduces the $/RPM and TOC as expected. Yet, the performance metrics are more positively influenced by the reduction in drag than any of the other factors as is evident by the greater slope. The reduction in wing weight has the larger impact on the manufacturing objectives since the wing weight is a primary contributor within ALCCA. Yet, the drag reduction has more of an impact on $/RPM and TOC. The use of the RDTE technology factor only influences the economic parameters and the utilization only the operational dependent metrics.

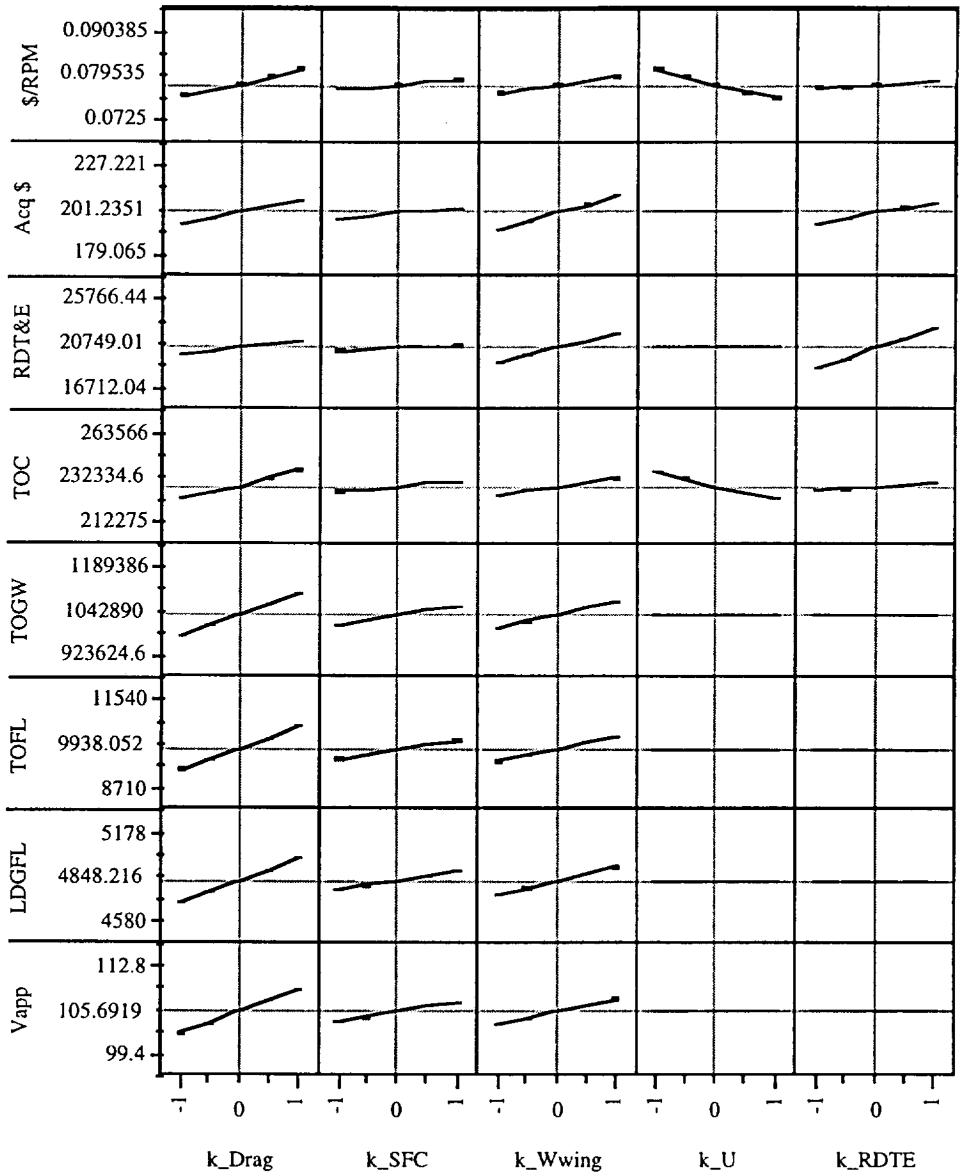


FIGURE 25: PREDICTION PROFILES FOR TECHNOLOGY "K" FACTORS

A comparison of the percent improvement of the objectives based on the three primary factors, i.e., k_Drag, k_SFC, and k_wing, with respect to the baseline was performed and summarized in Table VIII. The SFC improvement reduced the $/RPM by 0.95%, TOGW by 2.72%, and TOFL by 3.07%, and 1.27% in acquisition price from the conventional "optimal" configuration. The drag factor reduces TOGW by 7.83%, TOFL by 8.70%, $/RPM by 4.05%, and modest benefits to the acquisition price of 3.79%. The wing weight reduction affected the $/RPM objective by 3.15%. Substantial reduction was achieved for TOGW (6.27%), TOFL

(6.74%), and acquisition price by 11.0%. The SFC improvements were not as substantial as the wing weight and drag reductions. This is due to the fact that a 5% reduction in SFC would be a significant jump in propulsive technologies, whereas the wing weight and drag reduction projections are more attainable.

TABLE VIII: PERCENT IMPROVEMENTS WITH TECHNOLOGIES

Objective	Wing Wt	SFC	Drag
$/RPM	-3.15	-0.95	-4.05
Acquisition price	-8.09	-1.27	-3.79
TOGW	-6.27	-2.72	-7.83
TOFL	-6.74	-3.07	-8.70

Each of the above technology "k" factors improved the "optimal" point design solution, but of more importance is the improvement to the design space spanned by the variables in Table II and Table III. Hence, the FPI technique should again be applied to the design space for a given technology to assess the overall impact. For this study, only benefit will be assumed for a given technology. Future studies should include a correlation matrix of the various technology metrics. The matrix is needed since the various technologies are related. For example, if a drag reduction is desired in the form of laminar flow control, the aerodynamics of the system will be improved, yet, other systems will be negatively affected, such as SFC due to engine bleed, wing weight due to needed ducting, utilization due to higher maintenance requirements, etc. Some of these technologies were originally proposed for VLT-type concepts in references [8, 15, 16, 22, and 23].

Each of the above technologies (drag, SFC, and wing weight reductions) will be investigated with the FPI technique to identify which of the technologies most positively influences the design space.

4.2.1 Drag Reduction Technology

The technique applied for estimating feasibility and viability is utilized here to estimate the impact of drag reduction on the design space. CDFs were generated for all performance and economic metrics and are shown in Figure 26 through Figure 33. The TOGW metric was improved from a 0% probability of feasibility to a 4% probability due to drag reduction (Figure 26). Eventhough the probability value is small, the CDF is shifted closer to the target value of one million pounds. Furthermore, the TOFL was increased from a 21% for the conventional to 31% with the addition of this technology (Figure 27). Once again, the landing field length and approach speed CDFs were shifted to lower values as shown in Figure 28 and Figure 29, respectively.

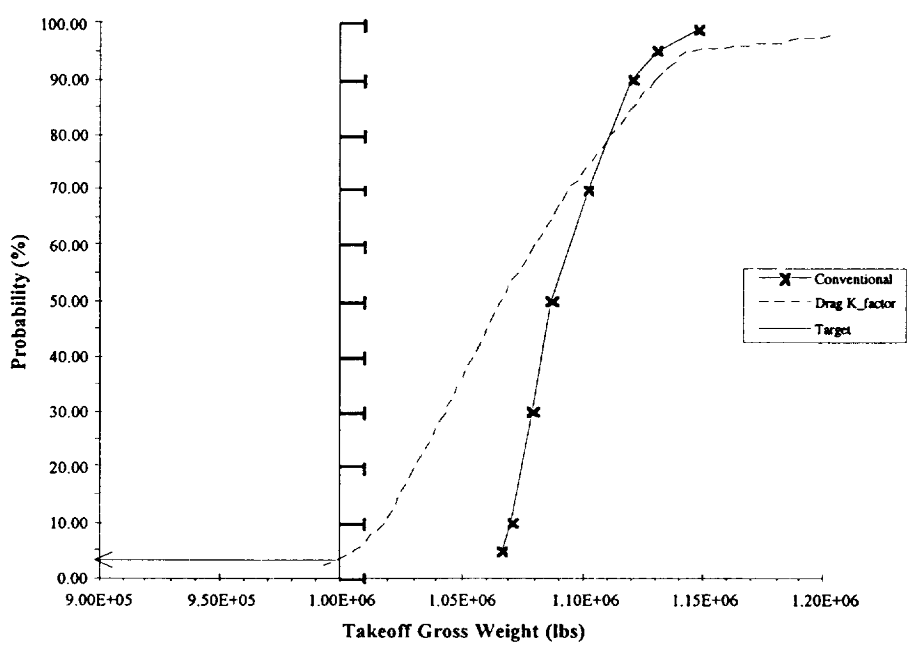


FIGURE 26: TOGW FEASIBILITY WITH DRAG "K" FACTOR

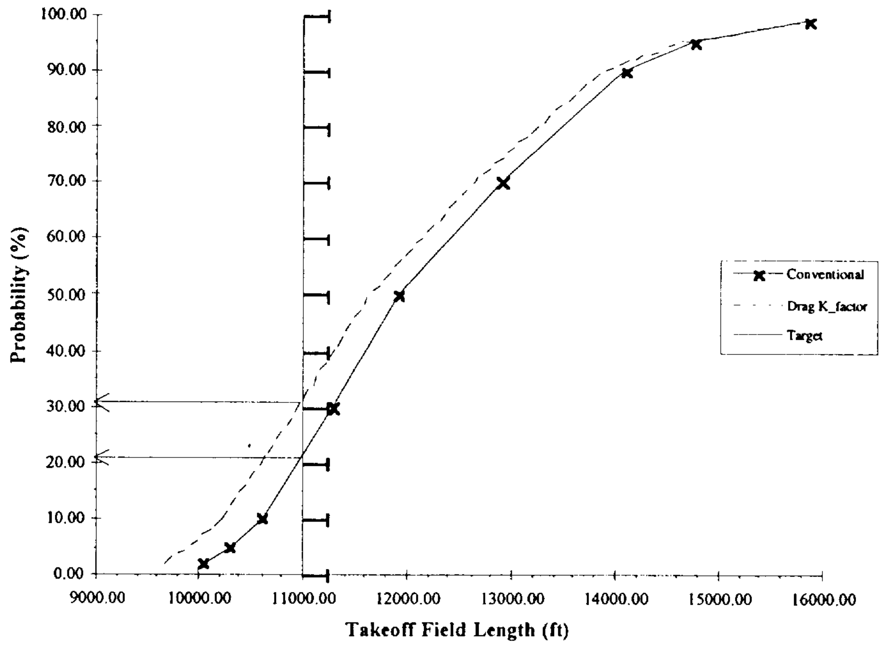


FIGURE 27: TOFL FEASIBILITY WITH DRAG "K" FACTOR

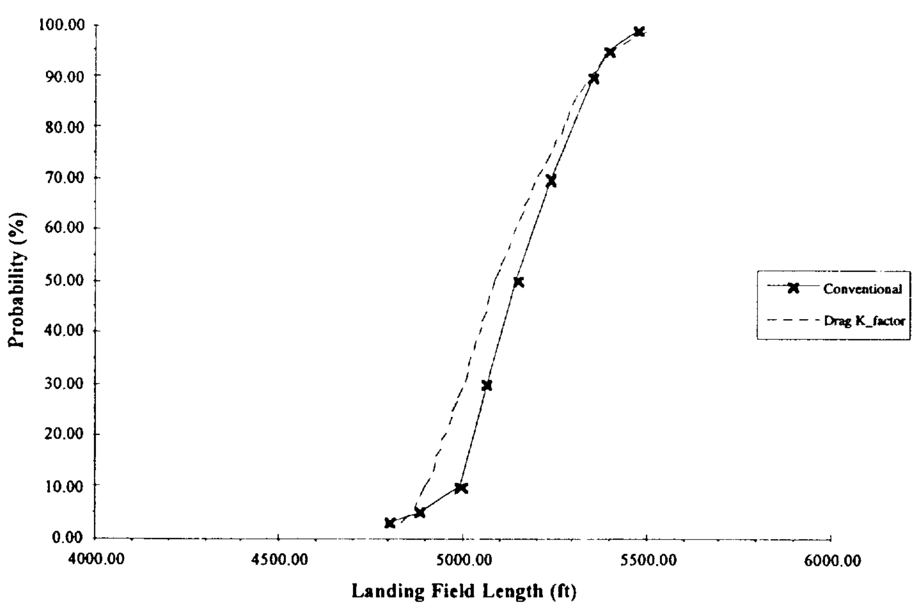


FIGURE 28: LDGFL FEASIBILITY WITH DRAG "K" FACTOR

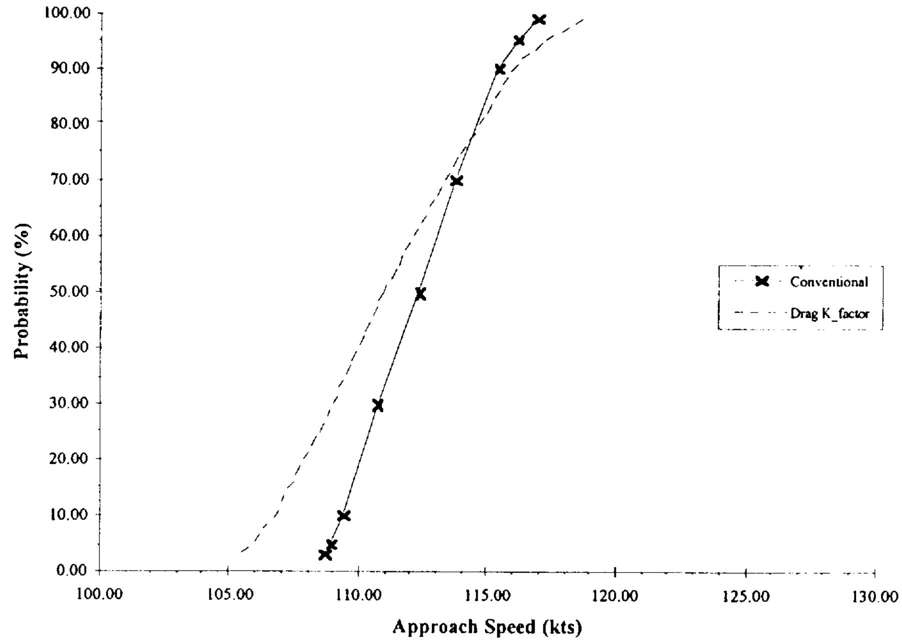


FIGURE 29: VAPP FEASIBILITY WITH DRAG "K" FACTOR

The economic viability of a VLT design space with drag reduction also improved. The $/RPM probability was increased from 66% for the conventional to 73% (Figure 30). A target probability of 70% was desired for viability which is achieved here. The acquisition price and TOC per trip also increased from 21% to 26% (Figure 31) and from 12% to 17% (Figure 33), respectively, while the RDTE simply moved closer to the target (Figure 32). It should be noted that the results obtained here are optimistic since the penalties to other systems was excluded.

The addition of a drag reduction technology can enhance the feasibility and viability of a VLT design space. Further studies should include the identification of actual technologies which could supply the needed aerodynamic improvements, and also include the penalties associated with other systems.

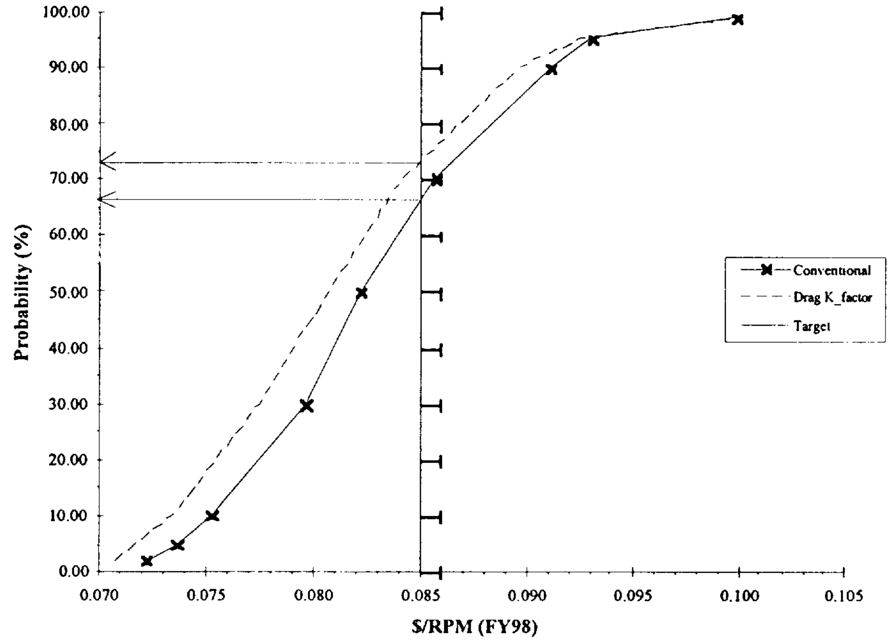


FIGURE 30: $/RPM VIABILITY WITH DRAG "K" FACTOR

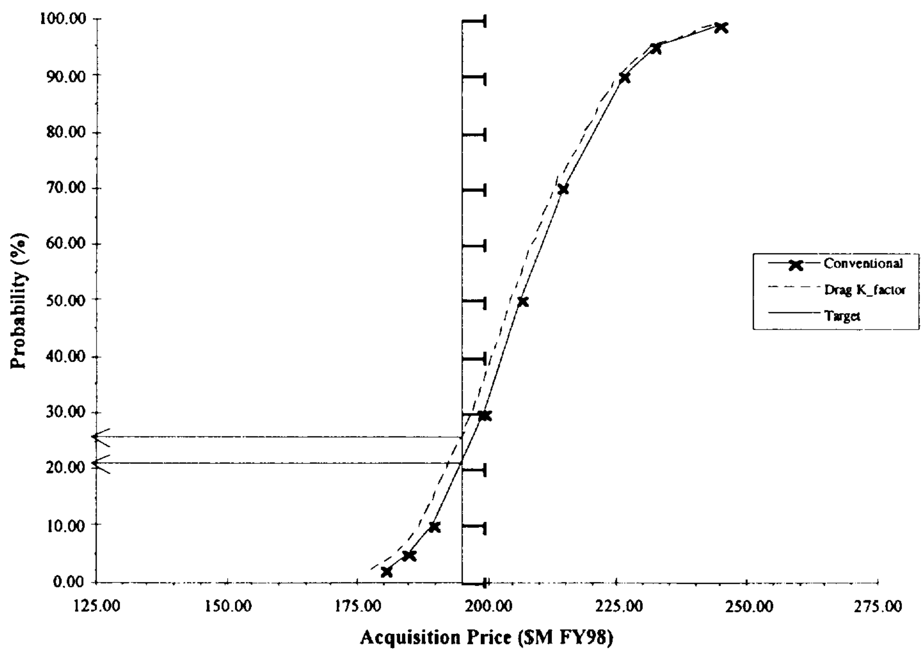


FIGURE 31: ACQ $ VIABILITY WITH DRAG "K" FACTOR

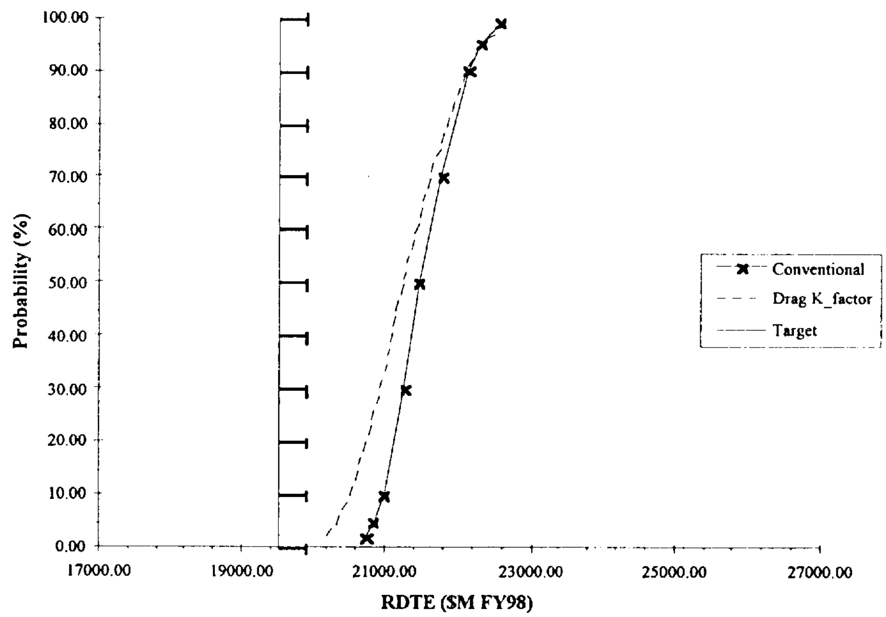


FIGURE 32: RDTE VIABILITY WITH DRAG "K" FACTOR

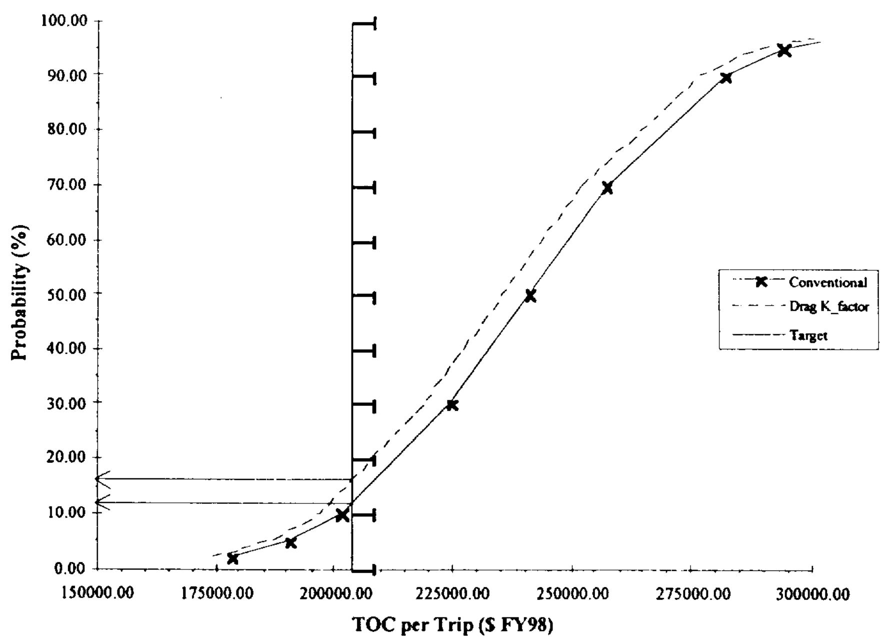


FIGURE 33: TOC VIABILITY WITH DRAG "K" FACTOR

4.2.1.1 Possible Technology: Laminar Flow Control

Still under experiment with NASA, laminar flow control shows great promise for reducing aircraft drag during cruise operations, thereby improving the overall aircraft lift-to-drag ratio (L/D) [22, 24, 25]. The primary mechanism for this technology is turbulent boundary layer suction thereby reducing drag. This technology is still in the infancy stages of its development and high risks are associated with the application. Yet, drag reduction, by as much as 10 to 15%, has been shown.

4.2.2 SFC Reduction Technology

The next technology to be investigated was the SFC reduction. As stated before, the SFC technology "k" factor was varied between ±5% from current day technology. FPI was applied with the control and noise variables with the addition of the SFC factor. The CDFs that resulted from the application are depicted in Figure 34 through Figure 41.

The technical feasibility was not significantly improved with the SFC reduction. In fact, the TOGW did not have any designs which were feasible as shown in Figure 34. Yet, the CDF was shifted closer to the target value. Actually, almost all of the performance and economic metrics were not improved. This fact is counter-intuitive. A 5% reduction in fuel flow should significantly impact the TOGW, TOFL, etc. This was shown in the prediction profile in Figure 25. The SFC could reduce the TOGW and TOFL by almost 3% for a 5% reduction. The reason for this discrepancy is within the mathematical formulation of the CDF approximation of FPI.

Within FPI, the CDF is estimated by initially approximating the CDF in a linear fashion. During this process, the sensitivity of a response to the deviation of a parameter is quantified. The sensitivity is based on perturbing a parameter from its mean value by approximately one-tenth of its standard deviation. Since a uniform distribution is assumed for the SFC, the standard deviation was 0.0289. FPI perturbed the SFC by 0.00289 and evaluated a very low sensitivity to SFC. Therefore, as FPI was building the CDF, the SFC improvements were minimal due to the initially low sensitivity values. The theory behind the model building is described in detail in

Reference [12]. One solution to this dilemma is to increase the range of the SFC factor to possibly ±10% which would in turn increase the standard deviation, and increase the sensitivity during the model building. Yet, if drastic improvements in feasibility and viability were shown, an actual technology would have to be identified which could deliver that proposed 10% improvement.

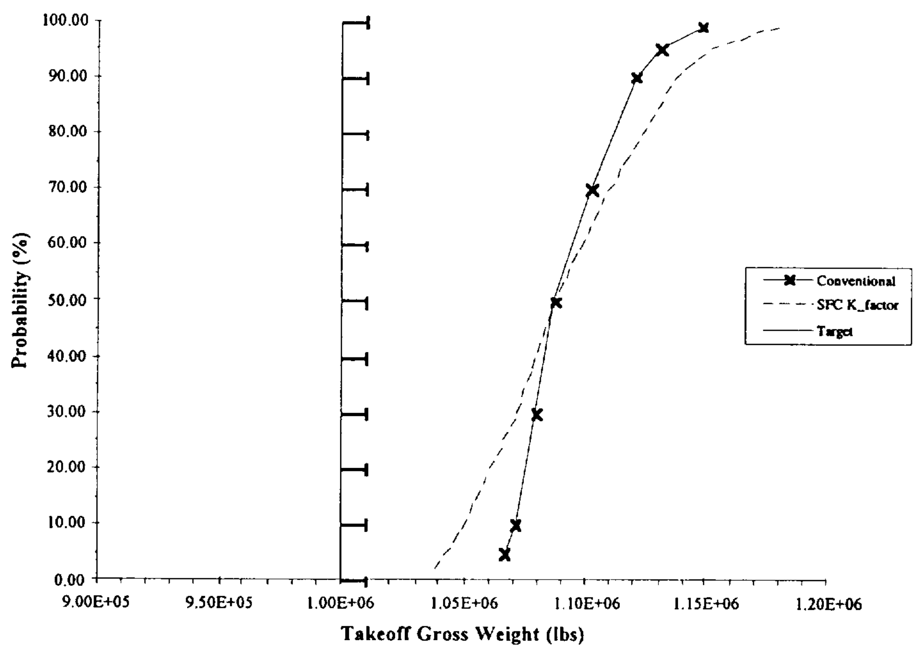


FIGURE 34: TOGW FEASIBILITY WITH SFC "K" FACTOR

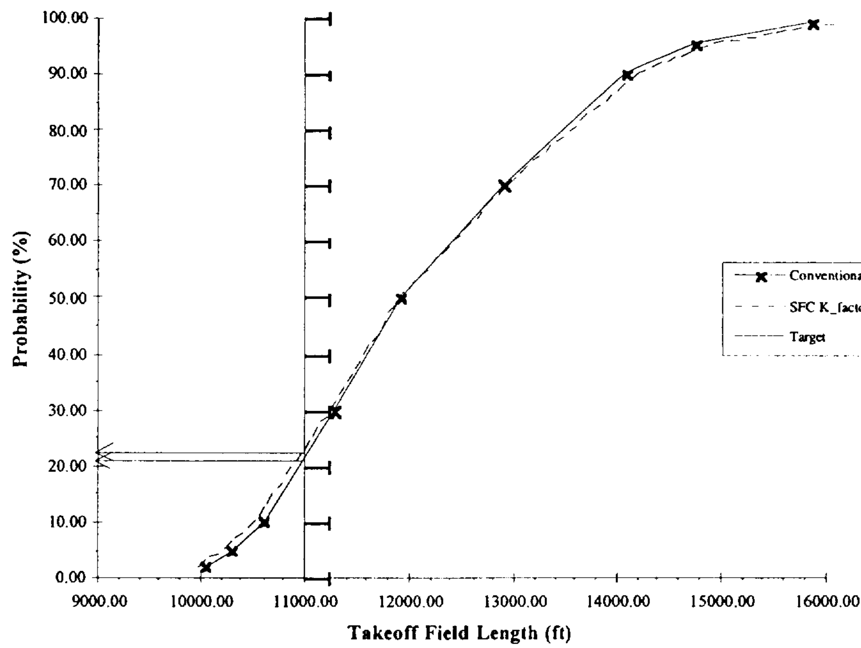


FIGURE 35: TOFL FEASIBILITY WITH SFC "K" FACTOR

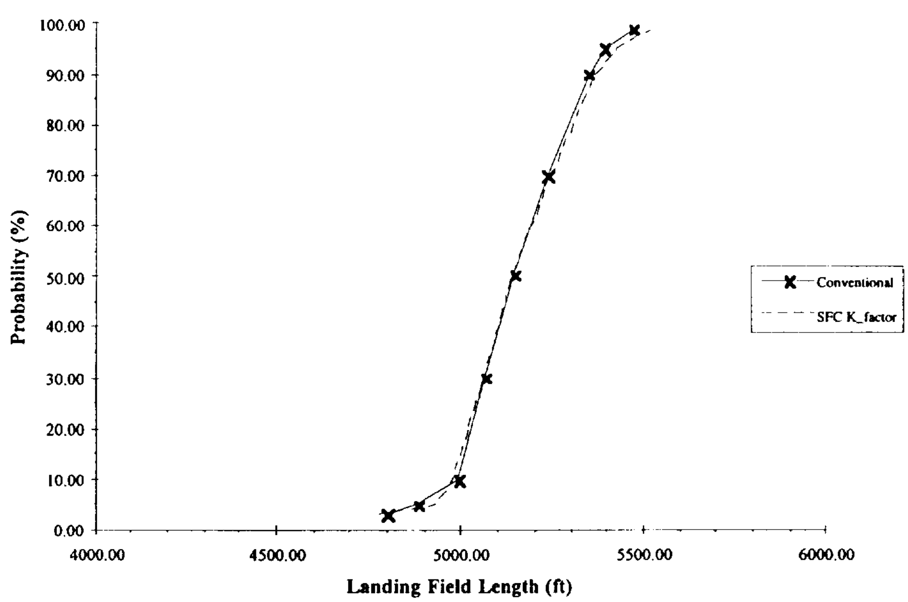


FIGURE 36: LDGFL FEASIBILITY WITH SFC "K" FACTOR

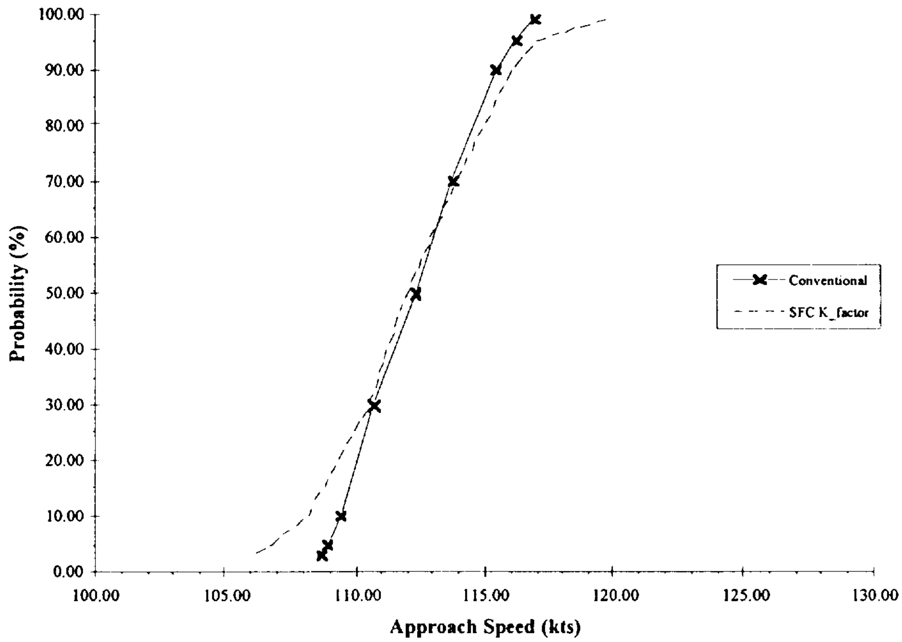


FIGURE 37: VAPP FEASIBILITY WITH SFC "K" FACTOR

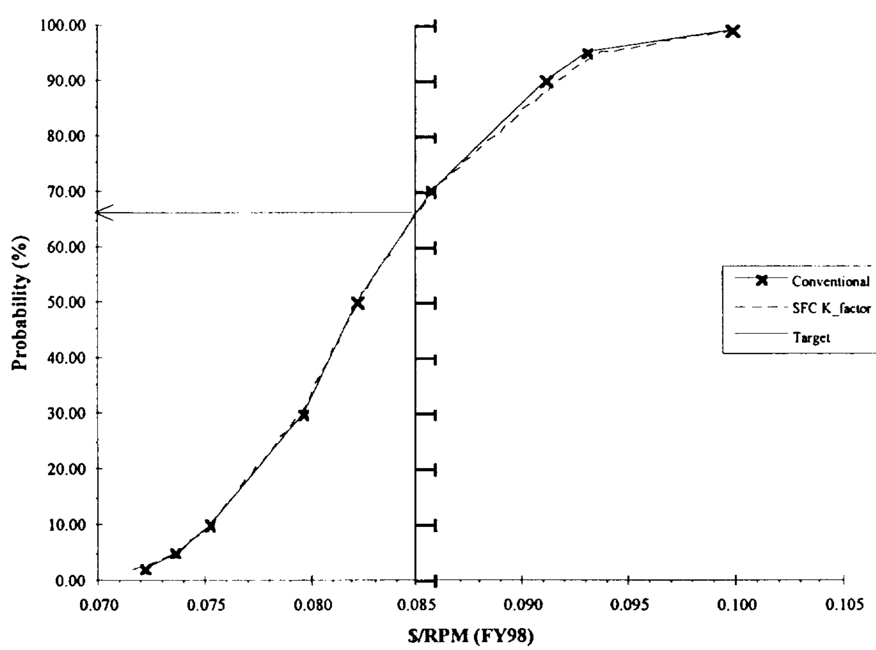


FIGURE 38: $/RPM VIABILITY WITH SFC "K" FACTOR

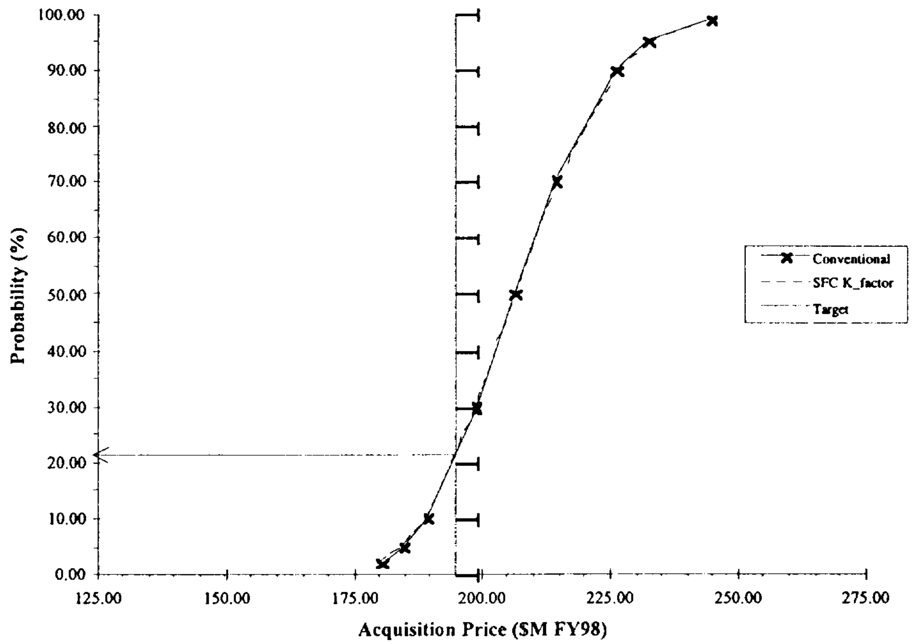


FIGURE 39: ACQ $ VIABILITY WITH SFC "K" FACTOR

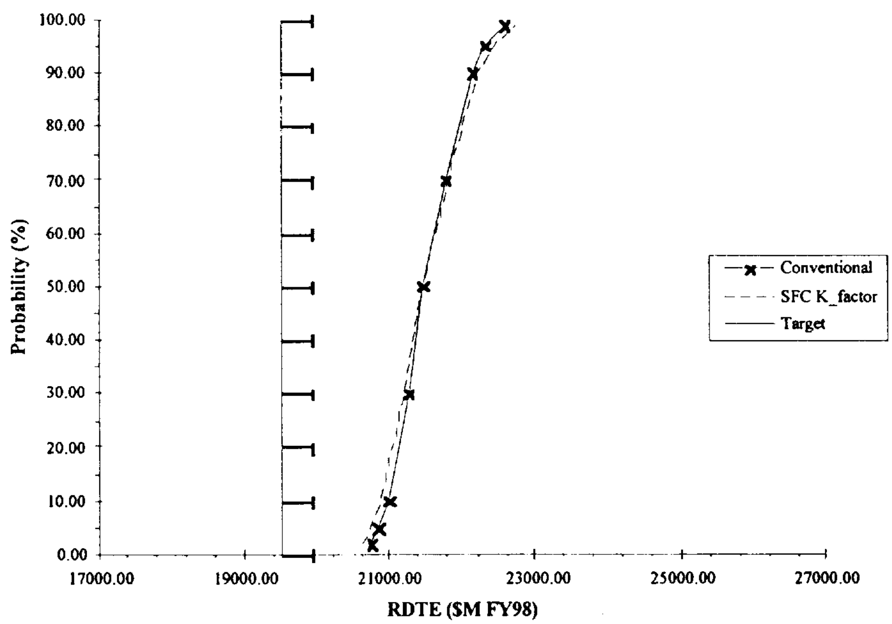


FIGURE 40: RDTE VIABILITY WITH SFC "K" FACTOR

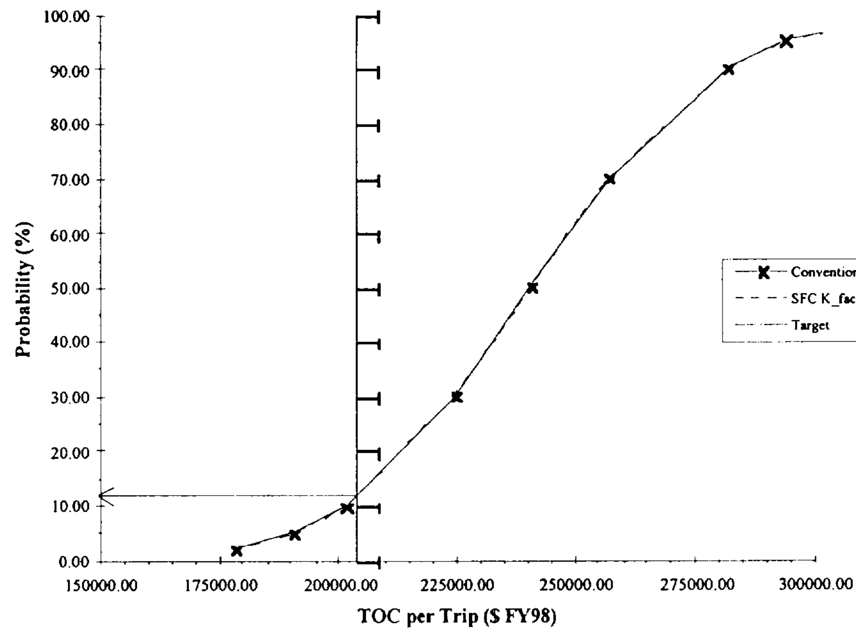


FIGURE 41: TOC VIABILITY WITH SFC "K" FACTOR

4.2.2.1 Possible Technology: Advanced Technology (AT) engine

An advanced engine is based on initiatives such as Improved High Pressure Turbine Engine Technology (IHPTET) engine advances. IHPTET is an Air Force initiative to improve the reliability and performance (SFC, engine weight) of future aircraft engines [23]. The goals of the IHPTET program are to achieve at least a 10% reduction in SFC. If this improvement could be obtained with minimal impact on other systems, the improvements in the design space could be more substantial than the results presented here. Yet, a pessimistic approach was taken for this study.

4.2.3 Wing Weight Reduction Technology

The final technology to be considered is wing weight reduction. The range of the technology "k" factor was a 30% reduction to a 5% increase. Once again, only the benefits with a reduction in wing weight is considered while penalties to other systems assumed negligible. The FPI technique was applied and CDFs generated as shown in Figure 42 through Figure 49.

Similar to the drag reduction, the wing weight reduction design space is now feasible with a 5% probability (Figure 42). Yet, more of the CDF has been shift towards the target. This trend is consistent for the TOFL (Figure 43), LDGFL (Figure 44), and Vapp (Figure 45). The TOFL probability was increased from 21% for the conventional and 31% for drag reduction to 37% for wing weight technology. From the three technologies considered thus far, the wing weight reduction has the most significant impact on the performance metrics within a VLT design space. Eventhough the effects screening test (Figure 25) showed that, for a point design, the drag reduction was the most significant, the wing weight reduction most positively influences the entire design space.

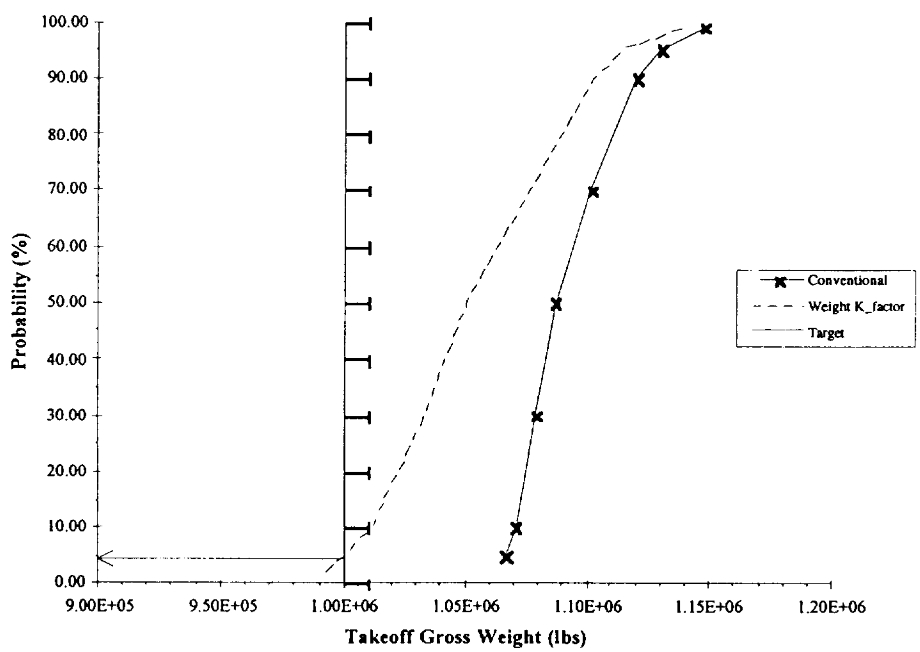


FIGURE 42: TOGW FEASIBILITY WITH WING WEIGHT "K" FACTOR

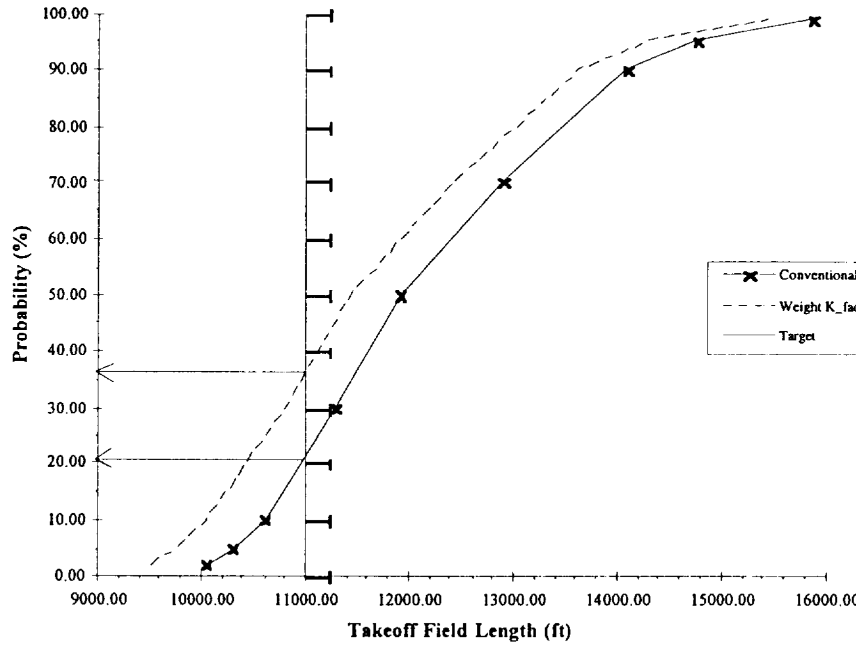


FIGURE 43: TOFL FEASIBILITY WITH WING WEIGHT "K" FACTOR

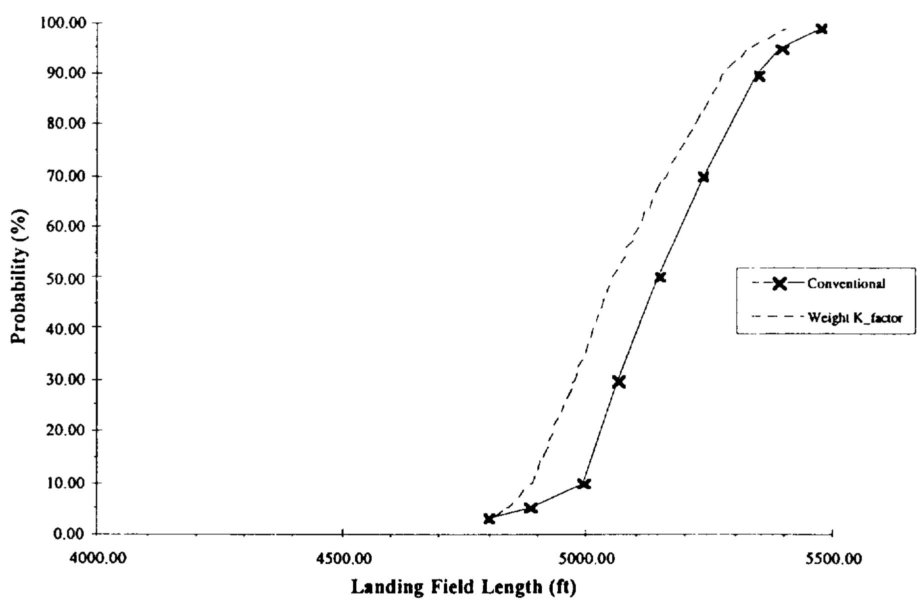


FIGURE 44: LDGFL FEASIBILITY WITH WING WEIGHT "K" FACTOR

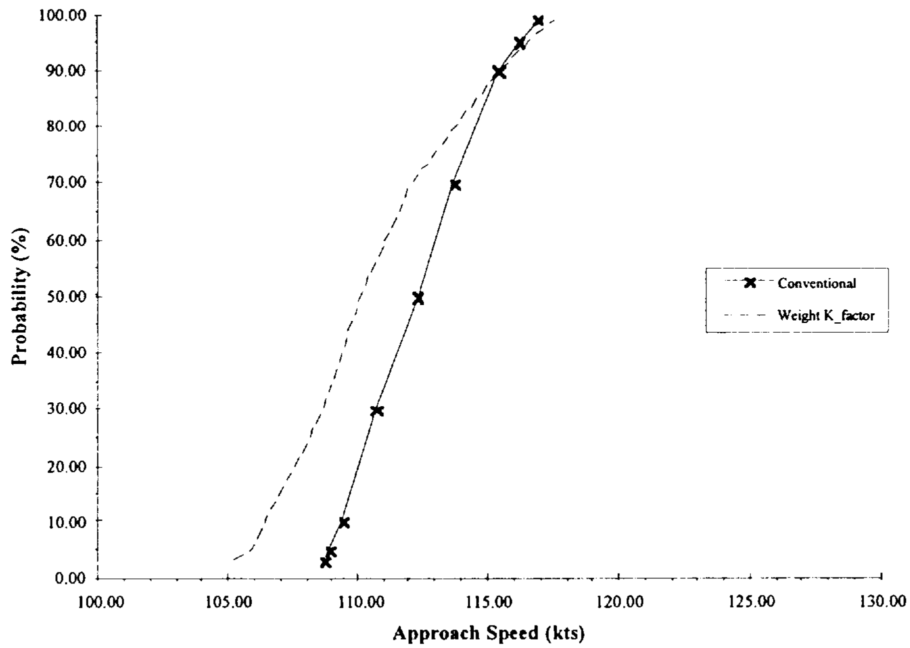


FIGURE 45: VAPP FEASIBILITY WITH WING WEIGHT "K" FACTOR

The economic viability of a VLT design space which incorporates some wing weight reduction technology is somewhat optimistic since penalties were not assumed for the manufacturing costs of some advanced materials or processes. With this in mind, the $/RPM probability was increased from 66% for the conventional design space to 73% (Figure 46). Hence, the economic target and the viability probability goal is achieved. Similarly, the acquisition price probability increased from 21% to 40% as shown in Figure 47. The TOC per trip probability only increased by 4% to a total of 16% (Figure 49). This small increase is indicative of the mild dependence on operating costs to system weights. If such factors as utilization or maintainability had been included, this change would be more significant. The largest improvements due to wing weight reduction are evident in the RDTE costs (Figure 48) where an 18% probability is achieved.

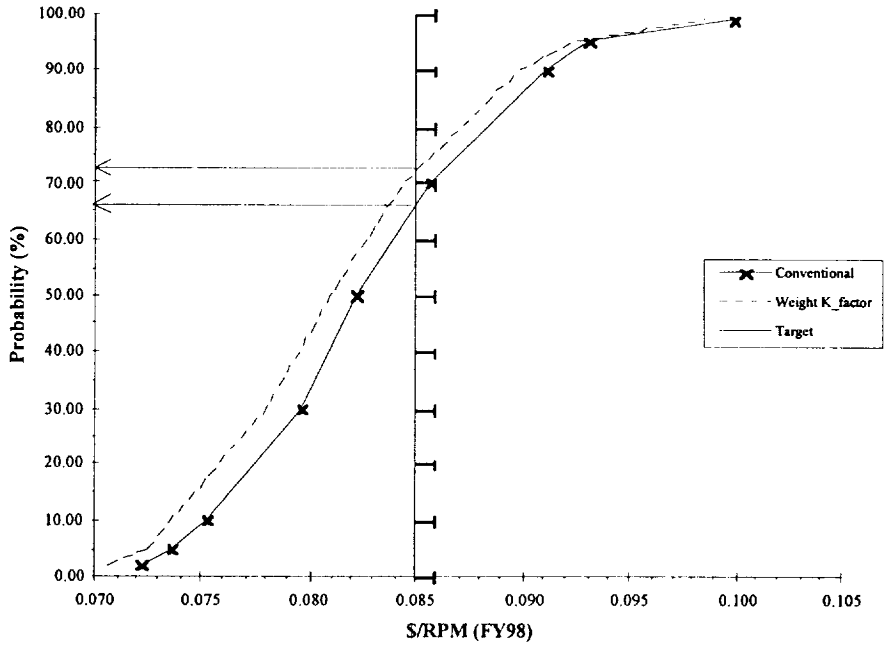


FIGURE 46: $/RPM VIABILITY WITH WING WEIGHT "K" FACTOR

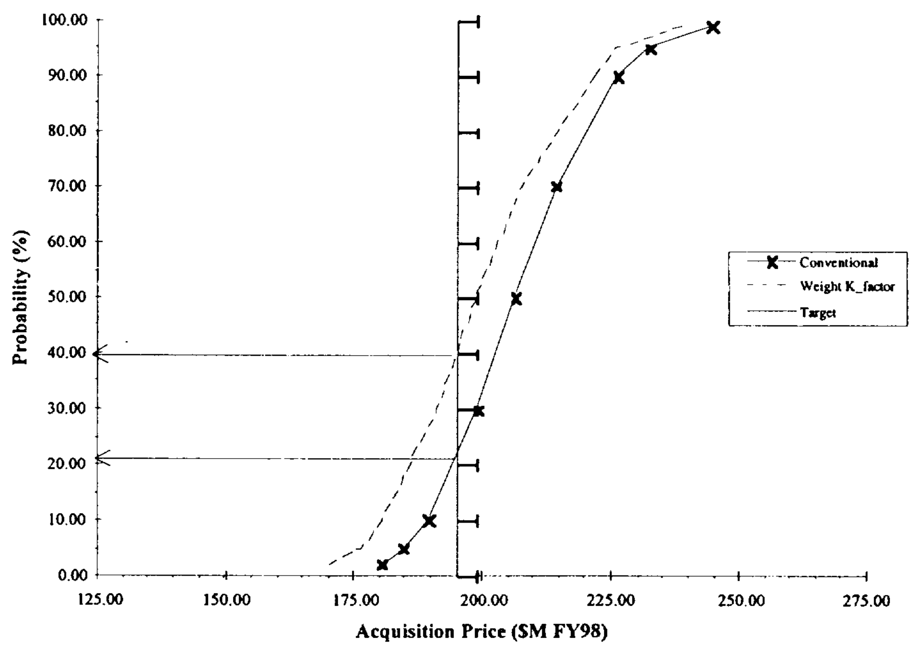


FIGURE 47: ACQ $ VIABILITY WITH WING WEIGHT "K" FACTOR

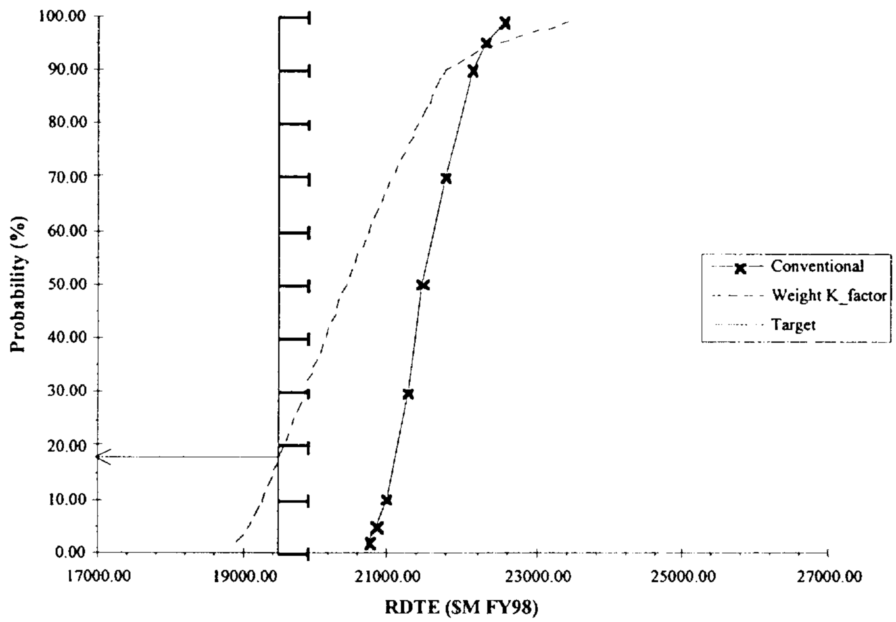


FIGURE 48: RDTE VIABILITY WITH WING WEIGHT "K" FACTOR

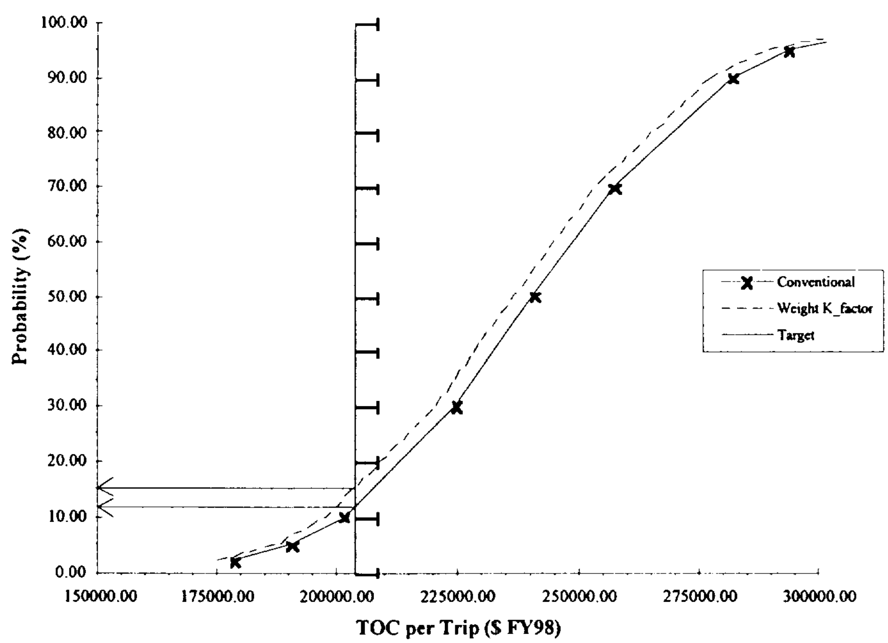


FIGURE 49: TOC VIABILITY WITH WING WEIGHT "K" FACTOR

4.2.3.1 Possible Technology: Composite Materials

The proposed weight reductions for the wing could be achieved through the use of various composite materials. Various materials have been proposed in references [26] which could deliver the desired 30% reduction in wing weight. Yet, composite use on a commercial transport is also in the infancy stage of maturation.

5. Conclusions

This investigation was an implementation of the modern aircraft design theory paradigm shift under development at the Aerospace Systems Design Laboratory. The implementation of this theory focused on identifying the technical feasibility and economic viability of a VLT concept utilizing the Fast Probability Integration technique. This technique approximated cumulative distribution functions (CDFs) of the objective probability values, as would typically be generated by a Monte Carlo simulation. These CDFs represented a design space which was then evaluated for feasibility and viability. Neither objective was achieved with a conventional, "baseline" VLT aircraft. Only through the addition of advanced technologies could a VLT satisfy the imposed performance and economic constraints. In particular, drag reductions were shown to have the most influence on the metrics of a point design, whereas the wing weight reduction had the most influence on the entire VLT design space.

This study also investigated the use of technology metrics in the form of "k" factors. Manipulation of these factors provided a means for identifying areas of possible technology infusion, so as to overcome design concept "show-stoppers." Improvements in specific fuel consumption, aerodynamics, and structural weights helped to expand the conventional configuration's design space into feasible and viable regions, with acceptable probabilities of success. The wing weight reductions were shown to have the most impact on the entire design space, while the drag reduction had more impact on a point design.

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