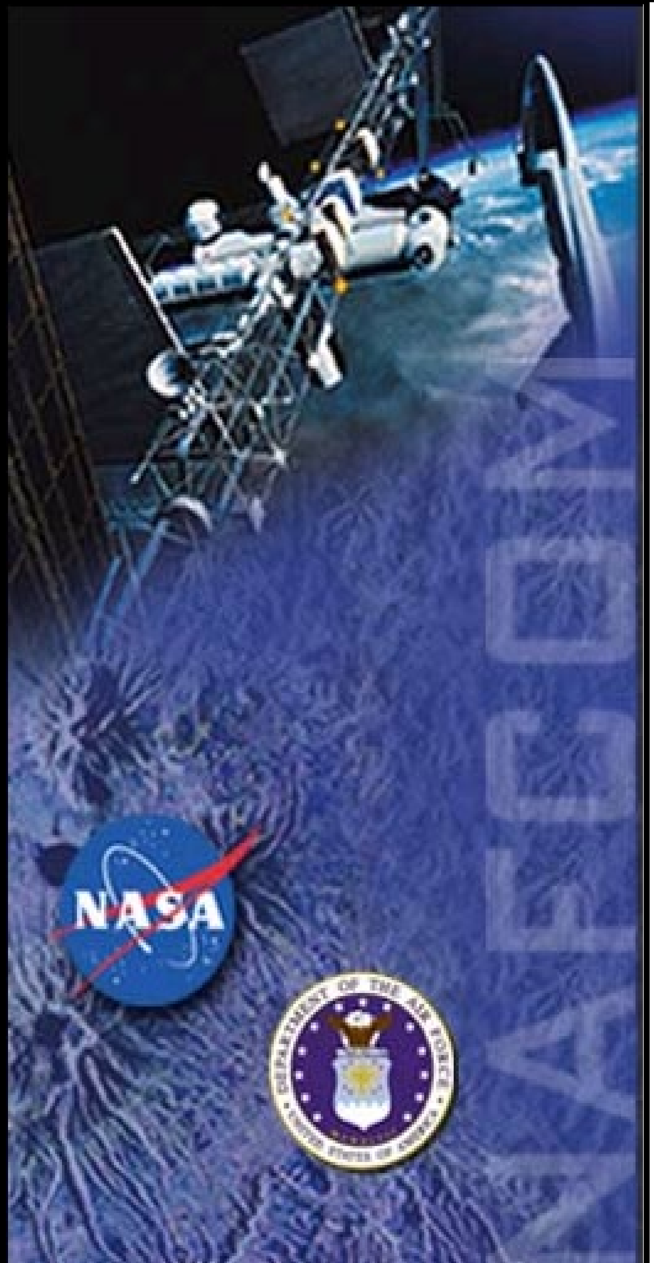

Risk Analysis in the NASA/Air Force Cost Model

Christian Smart, Ph.D., CCEA

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NAFCOM Description

- NAFCOM is a **parametric** estimating tool for space hardware.
- Uses **cost estimating relationships (CERs)** which correlate historical costs to mission characteristics to predict new project costs
- It is based on **historical** NASA and Air Force **space projects**
- It is intended to be used in the **very early phases** of a development project.
- NAFCOM can be used at the **subsystem or component** levels and estimates **development and production** costs.
- NAFCOM is applicable to various types of missions (**manned spacecraft, unmanned spacecraft, and launch vehicles**).
- There are two versions of the model: a **government version** that is restricted and a **contractor releasable version**.

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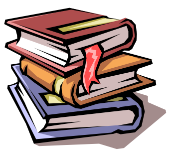
NAFCOM Evolution

NASA

- Since 1990, nine versions of NAFCOM have been developed and distributed across NASA and other government agencies.



NASCOM Books

NASCOM Automated DB

NASCOM Ver. 3.0 NASCOM Ver. 4.0

DEPARTMENT OF THE AIR FORCE • UNITED STATES OF AMERICA

NAFCOM96

NAFCOM99

NAFCOM Versions 2002 & 2004

1990

- NASCOM database in hardcopy only
- Estimators hand-entered data into spreadsheets
- Database contained 65 data points

1992

- Allowed online searches and copying of data
- Cost estimates developed in spreadsheets with CERs created by individuals
- Database contained 70 data points

1994

- Fully functional cost model with user defined WBS and data access
- CERs built automatically within NASCOM using "1st Pound" method
- Database contained 91 data points

1996

- Combined NASA and Air Force data
- Enhanced search and filtering of data
- Standardized WBS elements created
- Database contained 102 data points

1998

- First non-weight based CERs for five subsystems (Complexity Generators)
- Government and contractor versions distributed
- Database contained 114 data points

2000

- Total re-write of all NAFCOM program code
- Complexity Generators for all subsystems
- Major user interface improvements
- Database contains 122 data points

2002

- Cost Risk Analysis Module
- CER Improvements
- SOCM
- Component level Complexity Generator

2004

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Rationale

- Previously the NASA/Air Force Cost Model (NAFCOM) provided a point estimate as opposed to a probabilistic range estimate requiring external third party risk tools
- The addition of a probabilistic cost risk analysis module in NAFCOM v2004:
  - Integrates a comprehensive risk capability into NAFCOM including technical risk, cost equation uncertainty, and correlation
  - Provides a seamless and simple interface for accomplishing complete risk analysis of NAFCOM estimates

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Development

- Experts in the risk field, including representatives from MCR, Aerospace, NASA, IPAO, and Mitre participated in the methodology development.
- Dr. Steve Book and Erik Burgess of MCR worked directly with SAIC and NASA to ensure that the best possible approaches were considered for integration into NAFCOM and to consult on the methodology implementation.

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Model Selection

- Choice between Analytic approach (similar to FRISK) or Monte Carlo-based sampling approach
- We chose an analytic method because we wanted a method that:
  - Is computationally as simple as possible while still providing accurate estimates
  - Calculates the correct top-level means and standard deviations
  - Is faster than Monte Carlo
  - Allows full access to the correlation matrix
    - User can set individual inter- and intra-subsystem correlations to any desired value in the range (-1,1), unlike PRICE, SEER, and others

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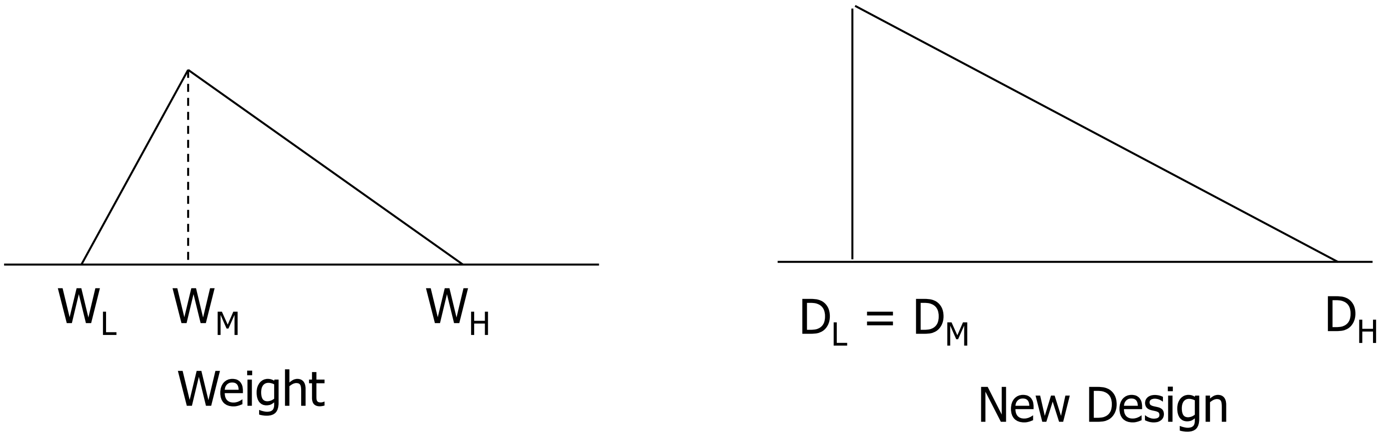
Technical Risk – Step 1

- For each WBS element (D&D and flight unit cost):
  - For each CER input*, define a triangular distribution using minimum value, most likely value, and maximum value



Note: NAFCOM multivariate CERs estimate cost at the subsystem or component level and have the general form:

Cost = C * Weight^{V}*New Design^{W}*Technical^{X}*Management^{Y} *Class^{Z}

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Technical Risk – Step 2

- Use appropriate CER to estimate costs for three cases: all complexity generators set to minimum (optimistic) values, all set to most likely, and all set to maximum (pessimistic) values

$$Low\,Cost = a \cdot W_L^{b_1} \cdot D_L^{b_2}$$

$$Most\,Likely\,Cost = a \cdot W_M^{b_1} \cdot D_M^{b_2}$$

$$High\,Cost = a \cdot W_H^{b_1} \cdot D_H^{b_2}$$

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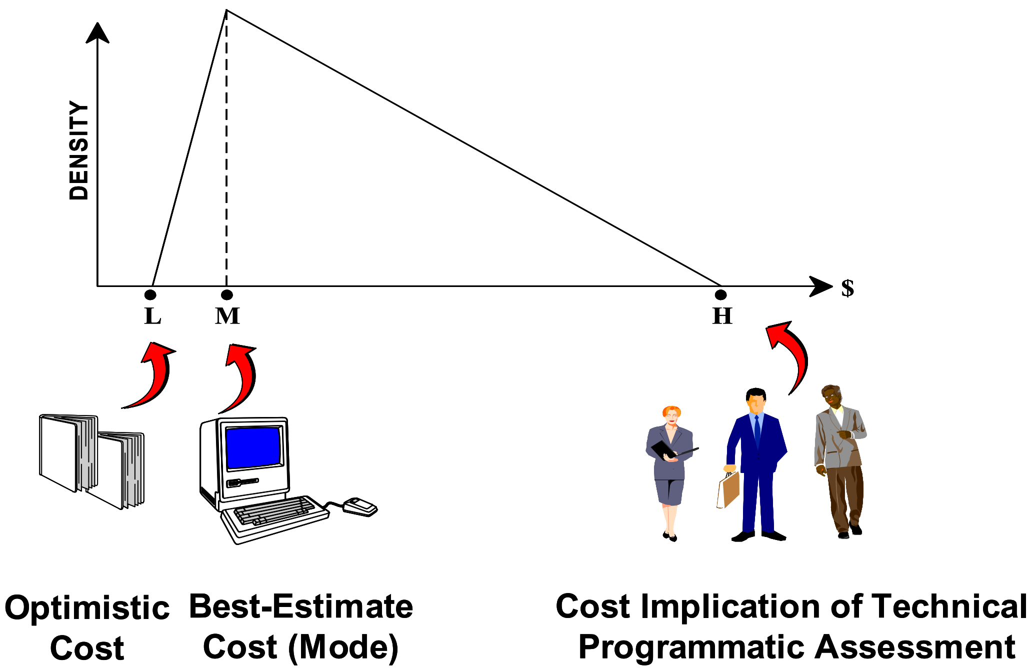
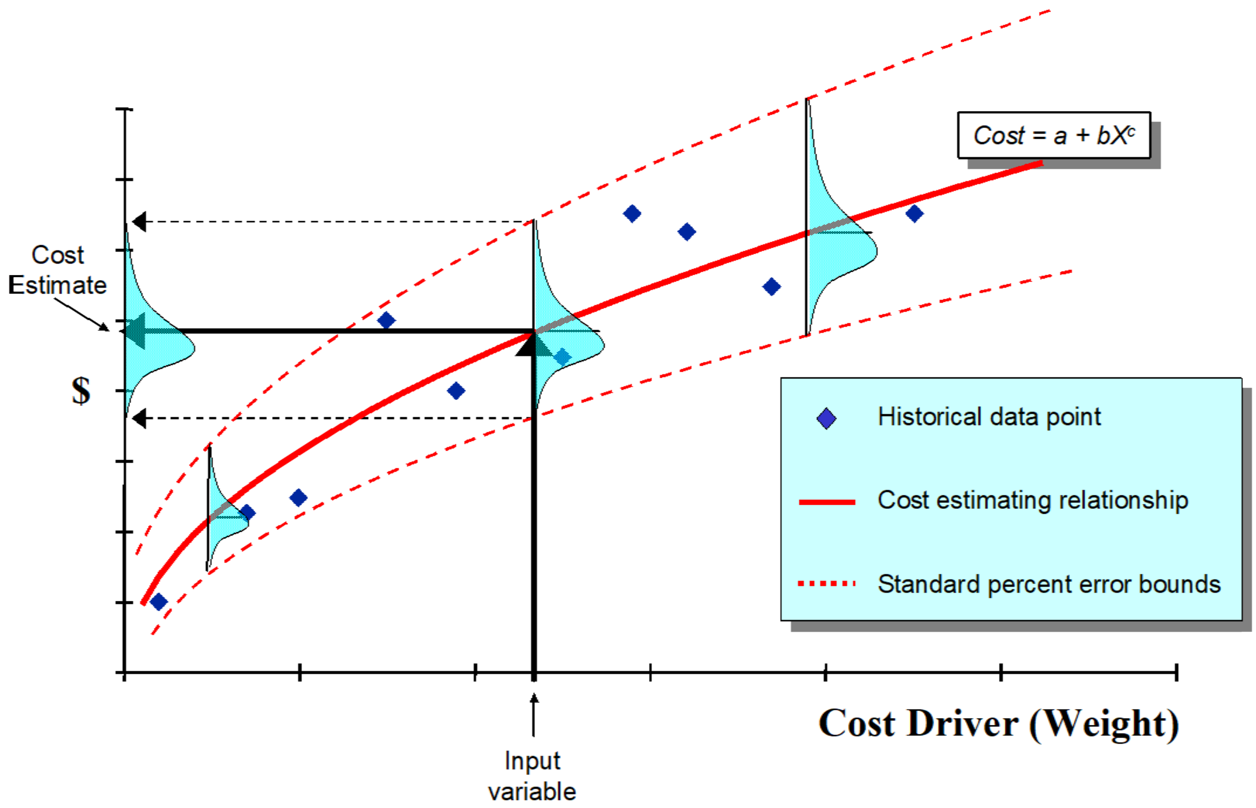
Technical Risk – Step 3

- Define a triangular distribution about each estimate with the minimum, most likely, and maximum values



CER Risk

- NAFCOM CER errors are lognormally distributed:



CER Risk

- NAFCOM CERs follow a multiplicative error model:

$$Y = aX^{b}\varepsilon$$

where e represents the error between the estimated cost $\hat{Y} = aX^{b}$ and the actual cost Y

- The error distribution of the CER is lognormal with median = 1 and standard deviation equal to the standard error of the CER

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CER Risk

- For each WBS element (D&D and flight unit cost):
  - Define a lognormal distribution using the median and standard error for the CERs
  - Fit a lognormal distribution to the first two moments (mean, standard deviation) of the technical risk triangular distribution defined on the previous page
  - Multiply the lognormal distribution of the CER error and the lognormal distribution defined in the preceding step – this product is a lognormal distribution
  - Calculate the DDT&E risk distribution mean and variance for each hardware element using the formula:

$$\mu = \mu_{D\&D} + (\%Flt\,Unit) * \mu_{Flt\,Unit}$$

$$\sigma^2 = \sigma^2_{D\&D} + (\%\,Flt\,Unit)^2 \sigma^2_{Flt\,Unit} + 0.2 * (\%Flt\,Unit) * \sigma_{D\&D} \sigma_{Flt\,Unit}$$

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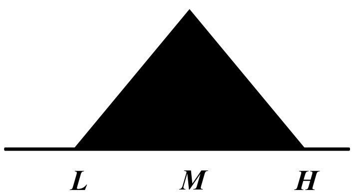
Combining CER and Technical Risk

At Estimating Level



Cost Implications of Complexity Drivers (Technical, Management and New Design)

P_1 , Q_1

X

$P_2 = 0$, Q_2 = S.E.

Distribution of Estimating Error

$$\mu = e^{P_1 + 0.5(Q_1^2 + Q_2^2)}$$

$$\sigma^2 = e^{2P_1 + Q_1^2 + Q_2^2}(e^{Q_1^2 + Q_2^2} - 1)$$

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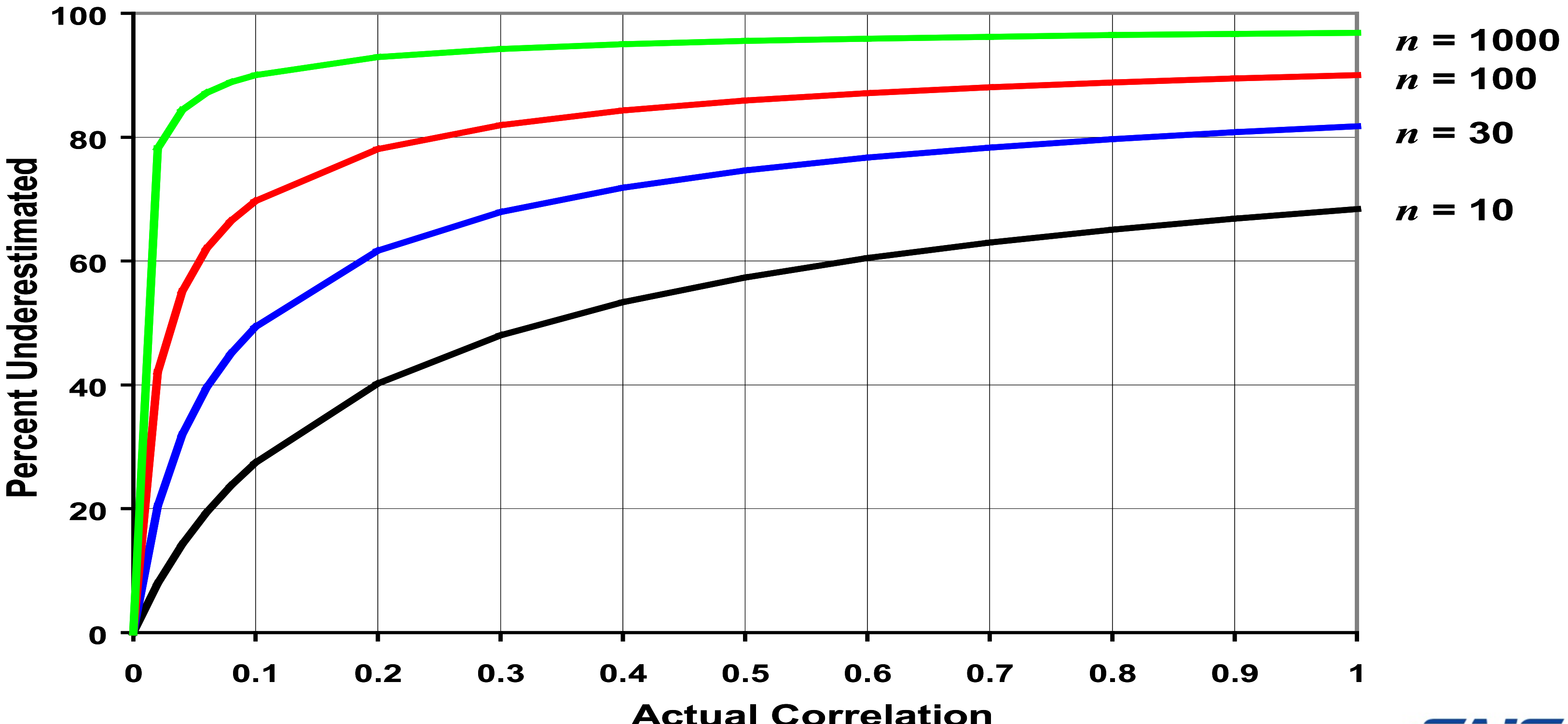
Correlation

Maximum Possible Underestimation of Total-Cost Sigma

Percent that Total-Cost Sigma is underestimated when correlation assumed to be 0 instead of ρ given *n* WBS elements



Reference: 32nd Annual DOD Cost Analysis Symposium Advanced Training Session, "Why Correlation Matters in Cost Estimating," Stephen A. Book

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Correlation in NAFCOM

- Set default values of the correlation matrix:
  - 0.2 for inter-subsystem and inter-system correlations
  - 0.5 for intra-subsystem correlations
- The user can set any of the correlations to any value between -1 and 1 he/she desires

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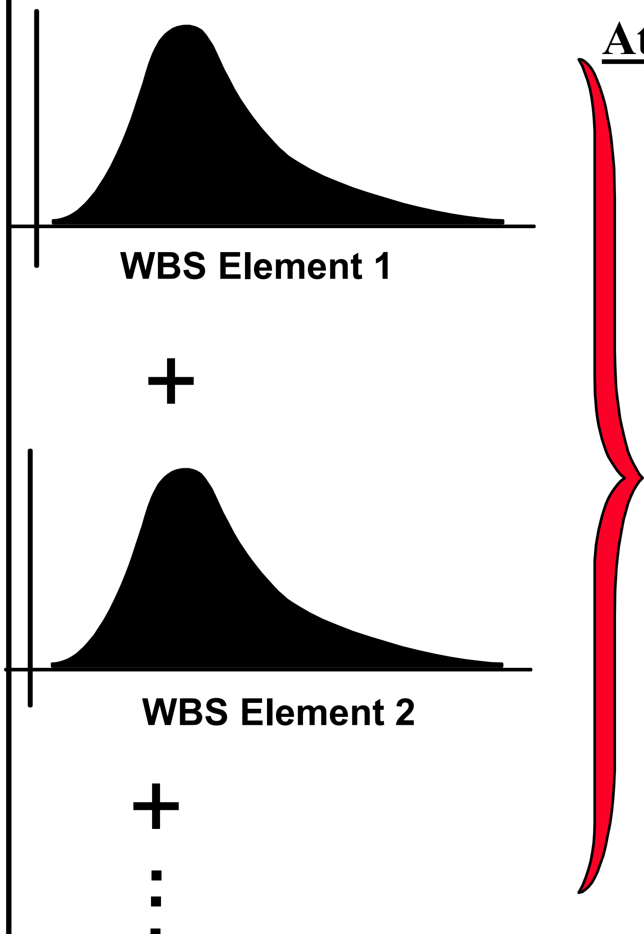
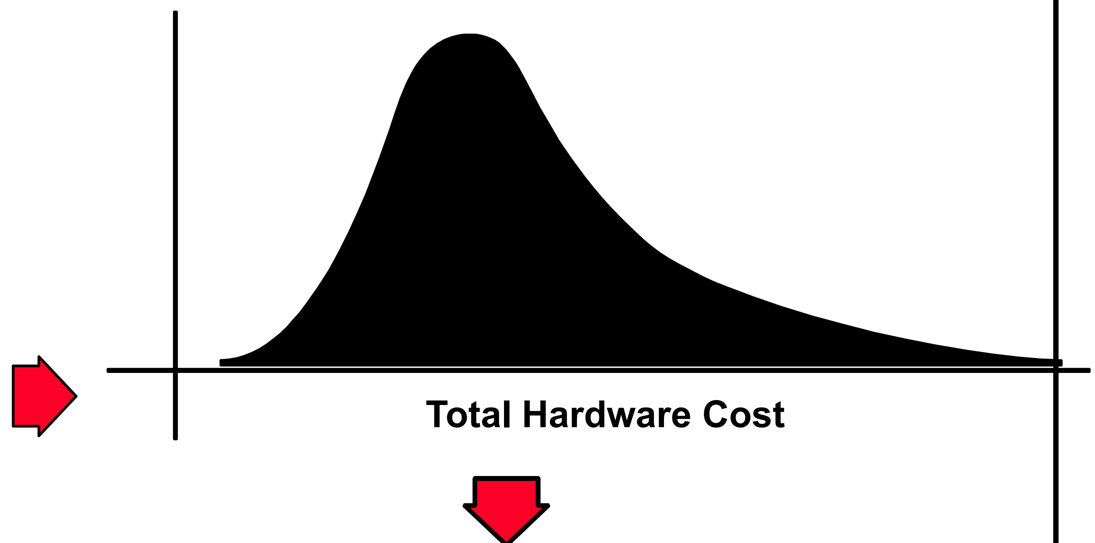
Summing Means and Variances



At Summation Levels



- **Approximate by lognormal or normal distribution**
- **Compute analytically**
  - **Mean**
  - **Mode ("Most likely")**
  - **Confidence percentiles**

Summing Means and Variances

Separately for DDT&E and flight unit cost, sum the mean and variance for all WBS items taking correlations (ρ_{ij}) into account

$X_1, \; X_2, \; \ldots, \; X_n$ are costs of WBS elements (considered as random variables)

Total (Hardware) Cost = $\sum_{k=1}^{n} X_k = X_1 + X_2 + \ldots + X_n$

Mean of Total (Hardware) Cost = $E\left(\sum_{k=1}^{n} X_k\right) = \sum_{k=1}^{n} E(X_k) = \sum_{k=1}^{n} \mu_k$

Variance of Total (Hardware) Cost =

$$Var\left(\sum_{k=1}^{n} X_k\right) = \sum_{k=1}^{n} \sigma_k^2 + 2\sum_{j=2}^{n} \sum_{i=1}^{j-1} \rho_{ij} \sigma_i \sigma_j$$

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Total Cost Distributions

- Fit a lognormal or normal distribution (chosen by the user) to the top level mean and variance
- Add the means and variances (including correlation) for the DDT&E and flight unit distributions to obtain a total cost distribution
- Outputs are the mean, median, mode, standard deviation, 5th, 10th,15th,…, 95th percentiles for DDT&E, flight unit, and total cost distributions

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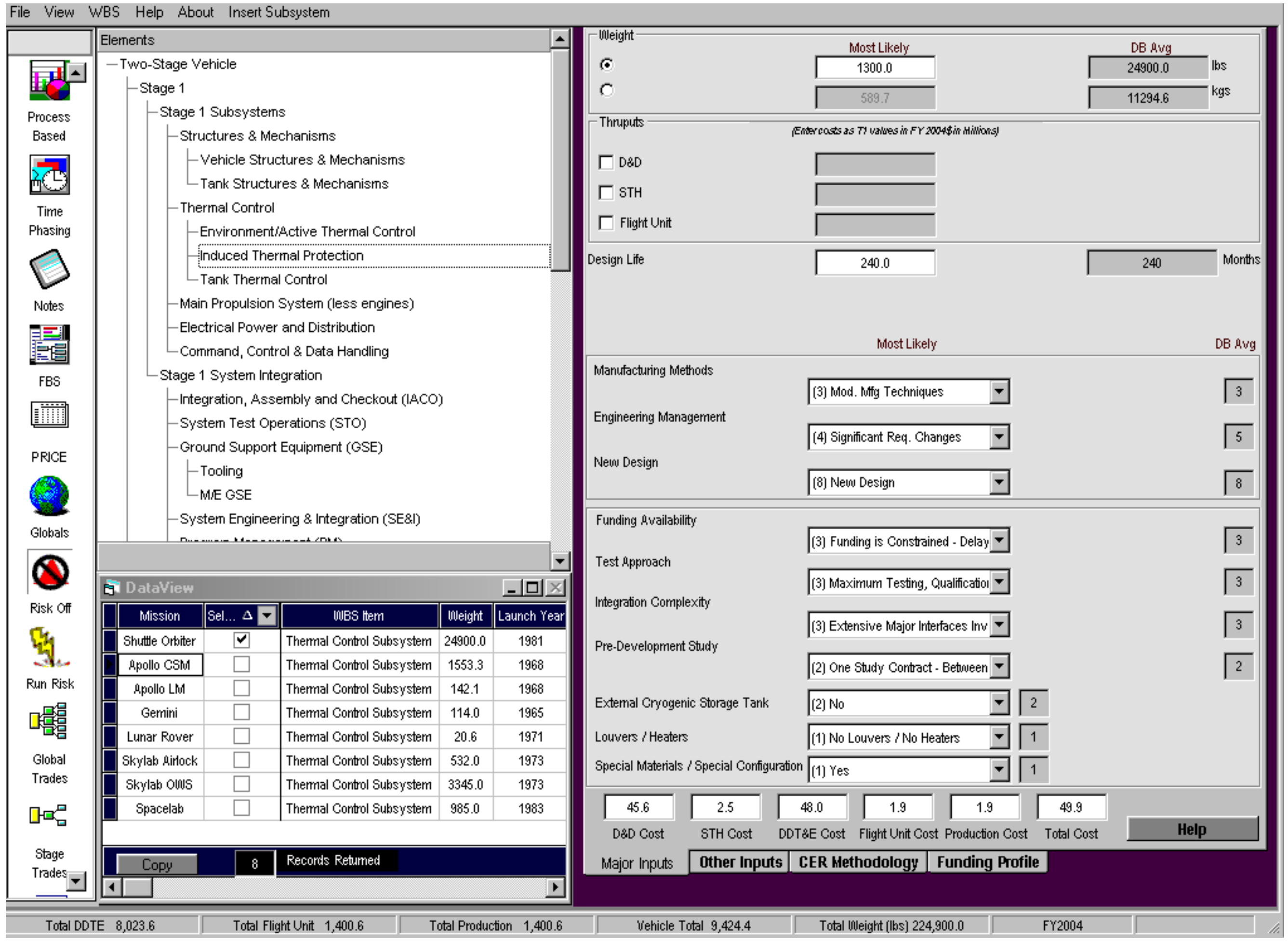
Model Interface

- Users can elect to run NAFCOM in Risk On or Risk Off mode via toolbar



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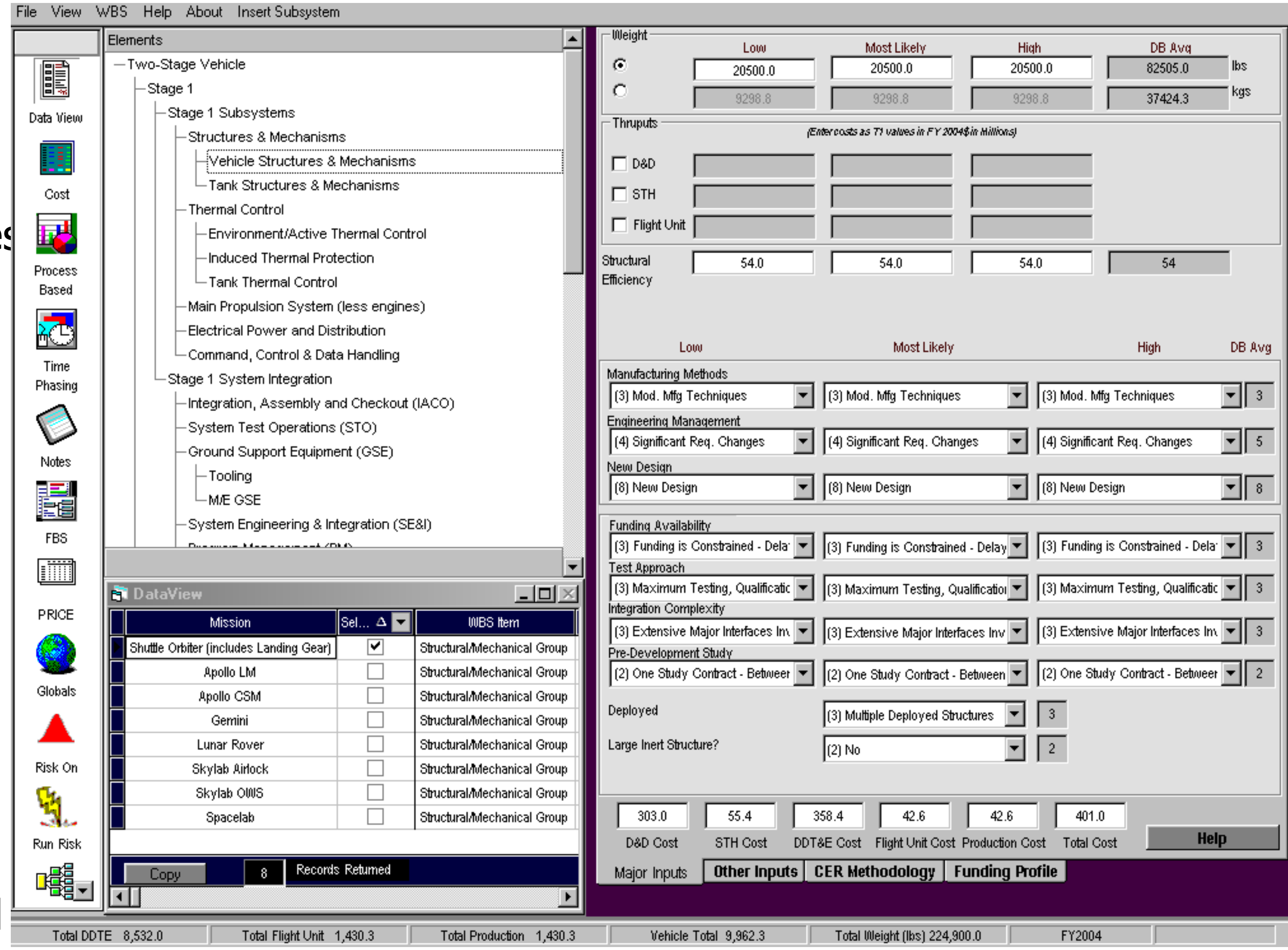
Model Interface

- NAFCOM's Risk On Mode provides capability to define triangular distributions for all cost driver inputs and for cost thruputs
- These distributions are combined with CER errors to produce distributions for nonrecurring and recurring cost for each subsystem



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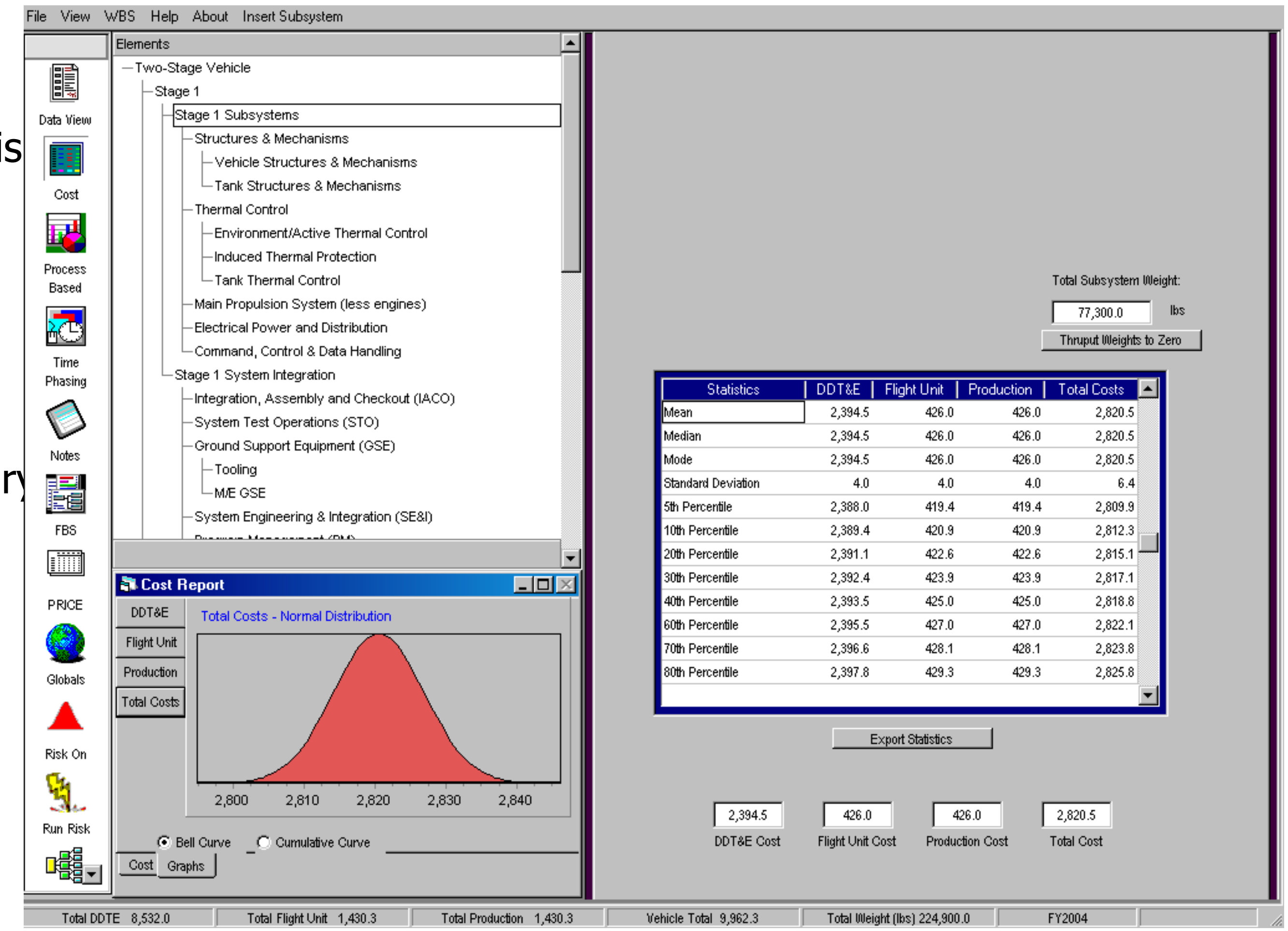
Model Interface

- The final result is uncertainty distributions for DDT&E, Flight Unit, Production and Total Cost.
- Result data includes summary statistics, probability densities, and cumulative distributions for each major estimating element (i.e. stage, bus)



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Risk Results Statistics – Example

Risk Results - Vehicle (2004 $ Millions)	DDTE	FU	Prod	Total
Mean	2374.2	465.2	673.8	3048.0
Median	2293.0	418.6	638.1	2962.2
Mode	2138.9	339.0	572.3	2797.8
Standard Deviation	637.4	225.5	228.5	738.8
5th Percentile	1485.8	196.6	370.9	1999.5
10th Percentile	1635.2	232.3	418.1	2180.8
20th Percentile	1836.4	284.4	483.4	2422.6
30th Percentile	1996.8	329.0	536.7	2613.3
40th Percentile	2144.8	372.6	586.9	2788.2
60th Percentile	2451.5	470.3	693.7	3147.1
70th Percentile	2633.3	532.7	758.6	3357.6
80th Percentile	2863.1	616.3	842.3	3622.1
90th Percentile	3215.5	754.3	973.8	4023.5
95th Percentile	3538.9	891.3	1097.8	4388.4

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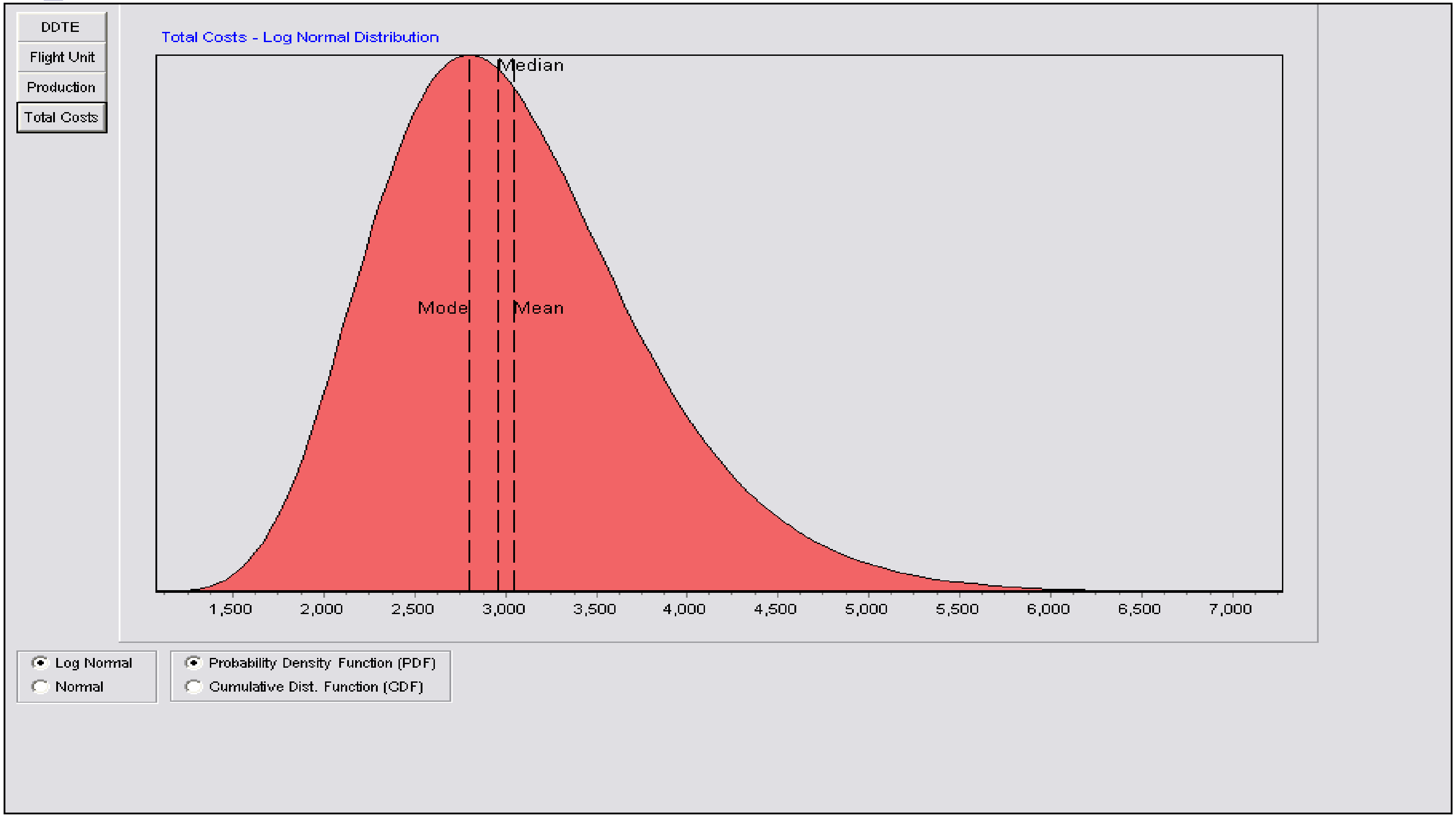
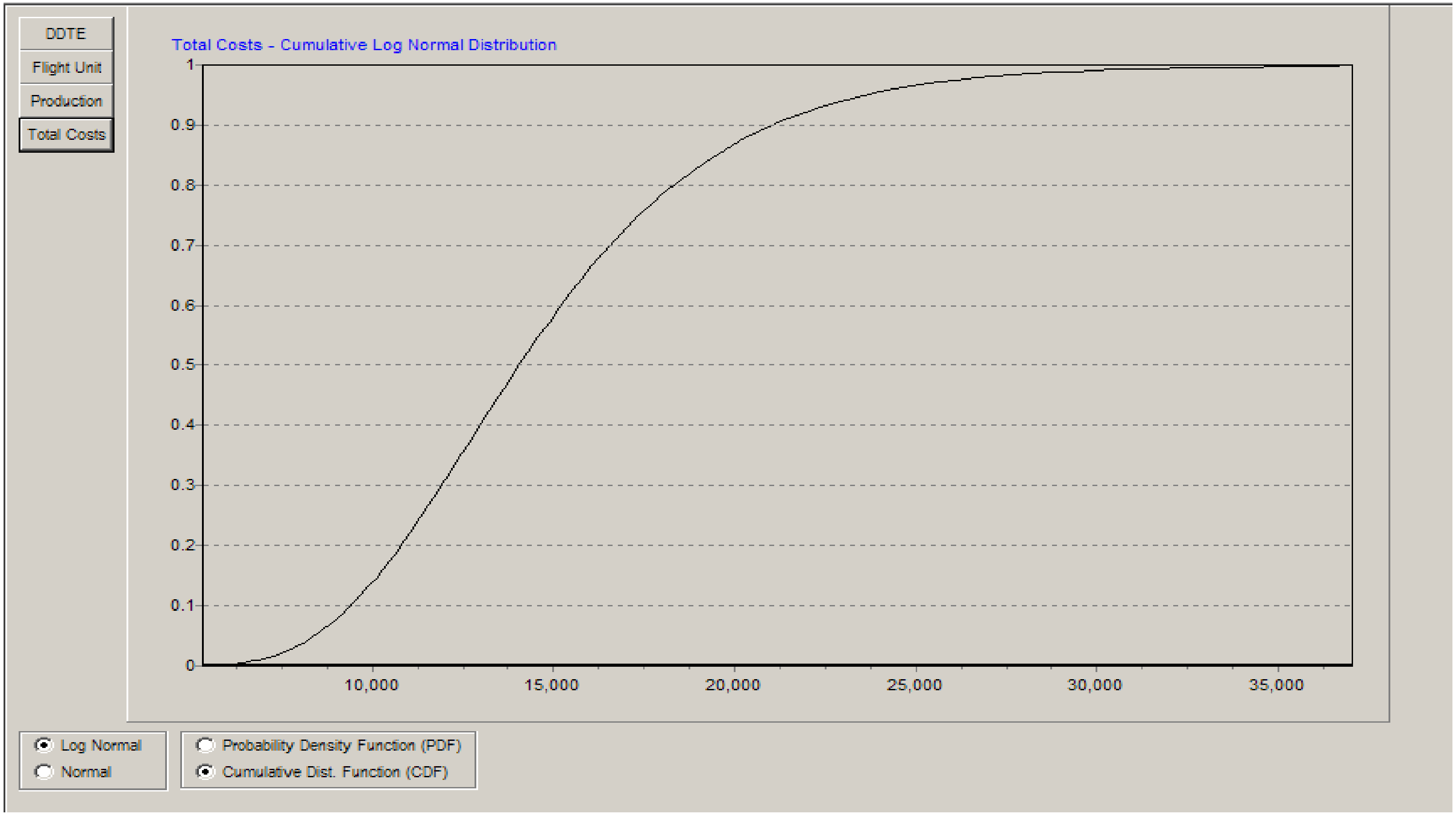
Risk Results PDF – Example



Risk Results CDF – Example



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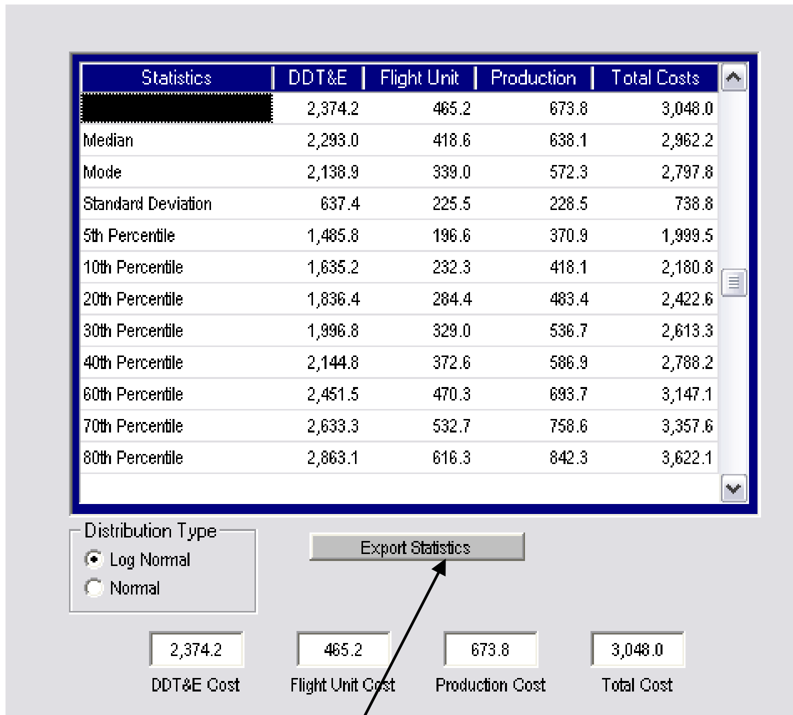
Saving Risk Output - Statistics



Statistics	DDT&E	Flight Unit	Production	Total Costs
[redacted]	2,374.2	465.2	673.8	3,048.0
Median	2,293.0	418.6	638.1	2,962.2
Mode	2,138.9	339.0	572.3	2,797.8
Standard Deviation	637.4	225.5	228.5	738.8
5th Percentile	1,485.8	196.6	370.9	1,999.5
10th Percentile	1,635.2	232.3	418.1	2,180.8
20th Percentile	1,836.4	284.4	483.4	2,422.6
30th Percentile	1,996.8	329.0	536.7	2,613.3
40th Percentile	2,144.8	372.6	586.9	2,788.2
60th Percentile	2,451.5	470.3	693.7	3,147.1
70th Percentile	2,633.3	532.7	758.6	3,357.6
80th Percentile	2,863.1	616.3	842.3	3,622.1

Click "Export Statistics"
To save to Excel

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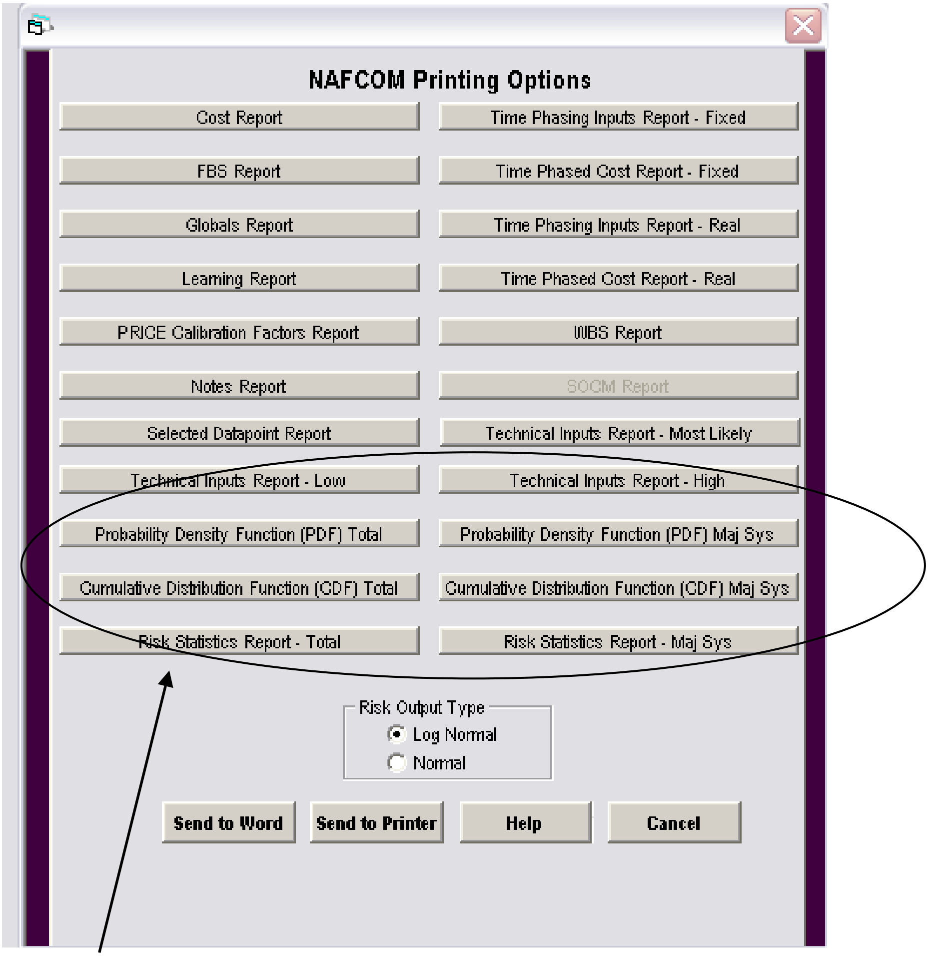
Generating Risk Reports



From the File Menu, Choose Printing Options, then one of the Risk Report Options

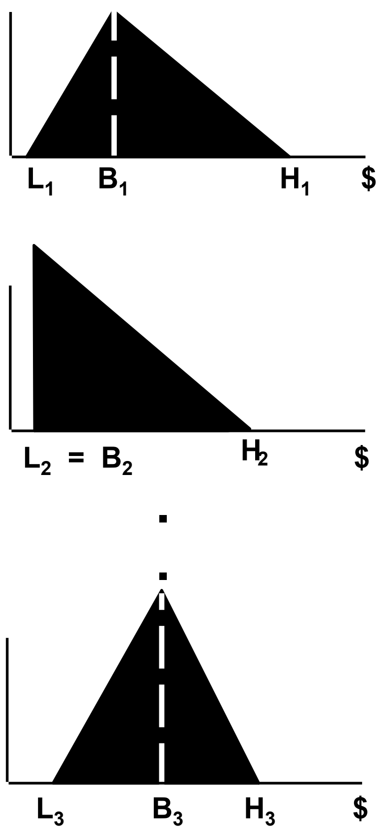
Risk Allocation to WBS Elements

- NAFCOM also provides the ability to determine which elements have the most cost risk associated with them and allocating risk dollars back to those WBS elements.
  - User may select a percentile (70th, 80th or 90th) to be used to determine the amount of risk dollars to be allocated to the WBS elements

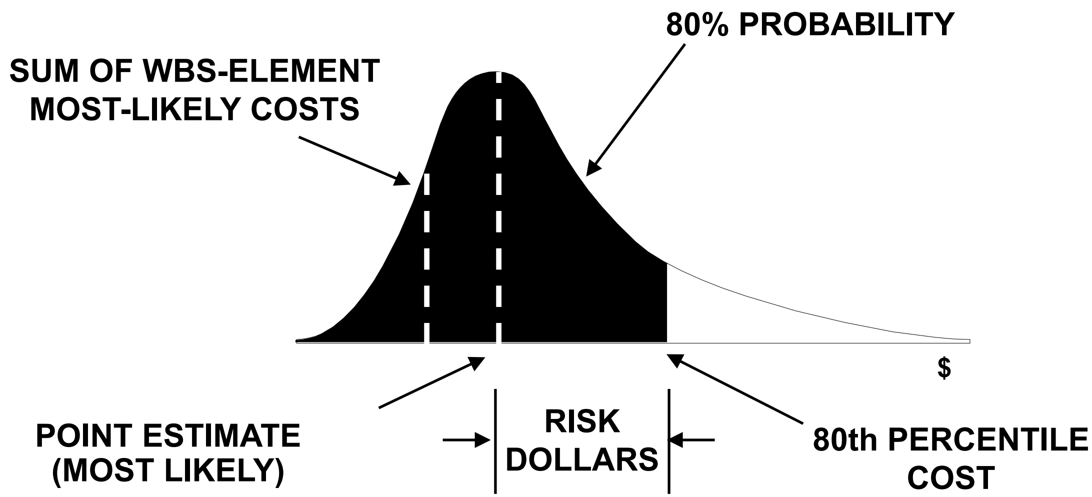
Reference: NSA Cost Performance Office Presentation, "Allocating 'Risk Dollars' Back to Individual Cost Elements," by Stephen A. Book, 2003

Risk Dollar Computation Procedure

Project-Element Triangular Distributions



Merge Element Cost Distributions Into Total-Cost Distribution



Note: ***Addition of risk dollars increases confidence that total appropriation (mean plus risk dollars) is sufficient to fund program.***

Reference: NSA Cost Performance Office Presentation, "Allocating 'Risk Dollars' Back to Individual Cost Elements," by Stephen A. Book, 2003

Allocating Risk Dollars Based on "Need"

- For each WBS element k = 1,…,N, the risk dollars are calculated as:

$$Risk\ Dollars(k) = \frac{ElementNeed(k)}{Need\ Base} * Risk\ Dollars$$

Reference: NSA Cost Performance Office Presentation, "Allocating 'Risk Dollars' Back to Individual Cost Elements," by Stephen A. Book, 2003

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Analytic Approximation Vs. Monte Carlo

- While there is no consensus on whether or not Monte Carlo is more accurate than analytic approximation, recent tests by Tecolote, MCR, and SAIC suggest that both methods provide similar results

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Comparison of Risk Model Output

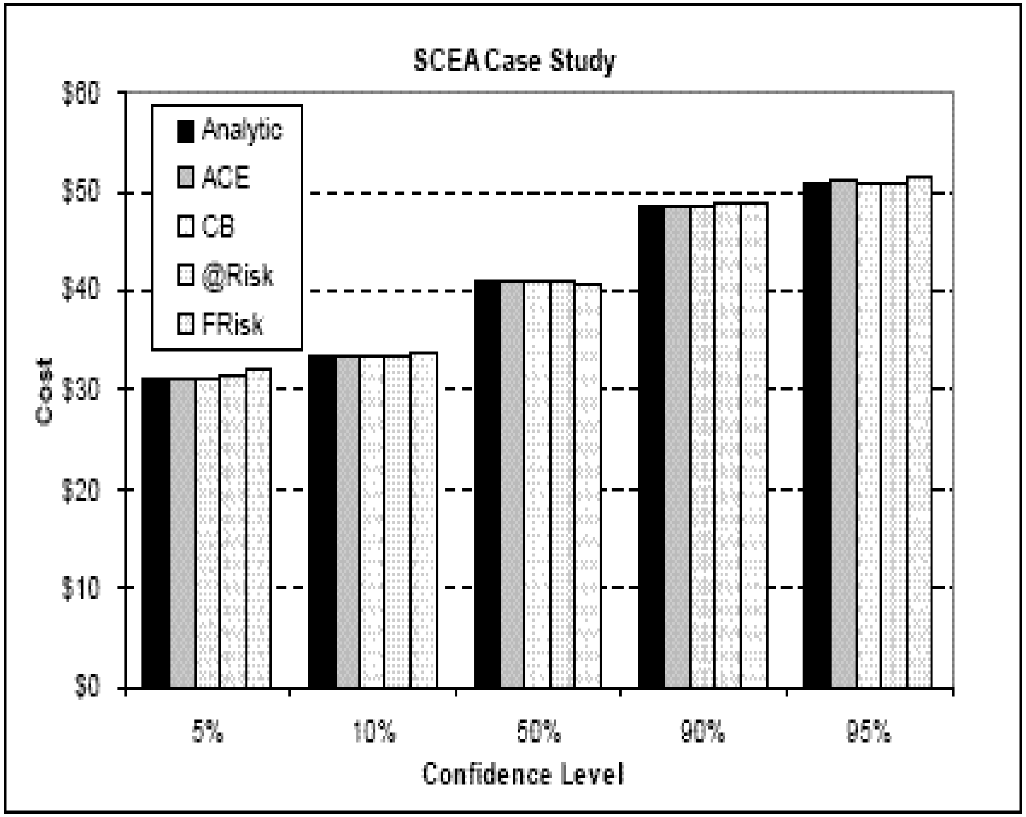

Figure 12: Comparing Risk Simulation Tools Based Upon 10,000 LHC Iterations.

Reference: SCEA Presentation "Cost Risk Analysis 'For the Masses'" by Tecolote Research, 2004.

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Comparative Risk Model Outputs for 2002 MCR Case Study

Table 6: MCR Case Study

	Sd	5%	10%	50%	90%	95%
ACE	487.2	1,043	1,156	1,708	2,438	2,630
CB	486.1	1,044	1,157	1,704	2,441	2,626
@Risk	489.9	1,039	1,150	1,705	2,448	2,640
Normal	491.8	947	1,126	1,756	2,386	2,565
FRISK	491.8	1,076	1,189	1,691	2,405	2,657
Beta	491.8	994	1,121	1,729	2,431	2,610

Reference: SCEA Presentation "Cost Risk Analysis 'For the Masses'" by Tecolote Research, 2004.

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NAFCOM Case Studies

- SAIC worked with Erik Burgess of MCR to compare the NAFCOM analytic approximation algorithm with Monte Carlo simulation
- We compiled four test cases and analyzed each using both Monte Carlo and analytic approximation
- Monte Carlo simulations were performed in @Risk, using 10,000 trials
- @Risk uses rank correlation, so the Monte Carlo results underestimate the standard deviation and thus slightly underestimate the risk

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Results Summary

- Comparisons are very favorable
  - Even for the case with the most variance, the differences in means is less than 1%
  - All percentiles are within 12%
- Results for tails are as expected
  - Monte Carlo tails are thinner than NAFCOM
    - Expected because @Risk uses rank correlation
- Nothing significant would be gained from implementing Monte Carlo approach

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Test Case 1

- Single Stage Vehicle
- Hardware Only
- Four Subsystems
  - Structures
  - Thermal Control
  - EPD&C
  - CC&DH

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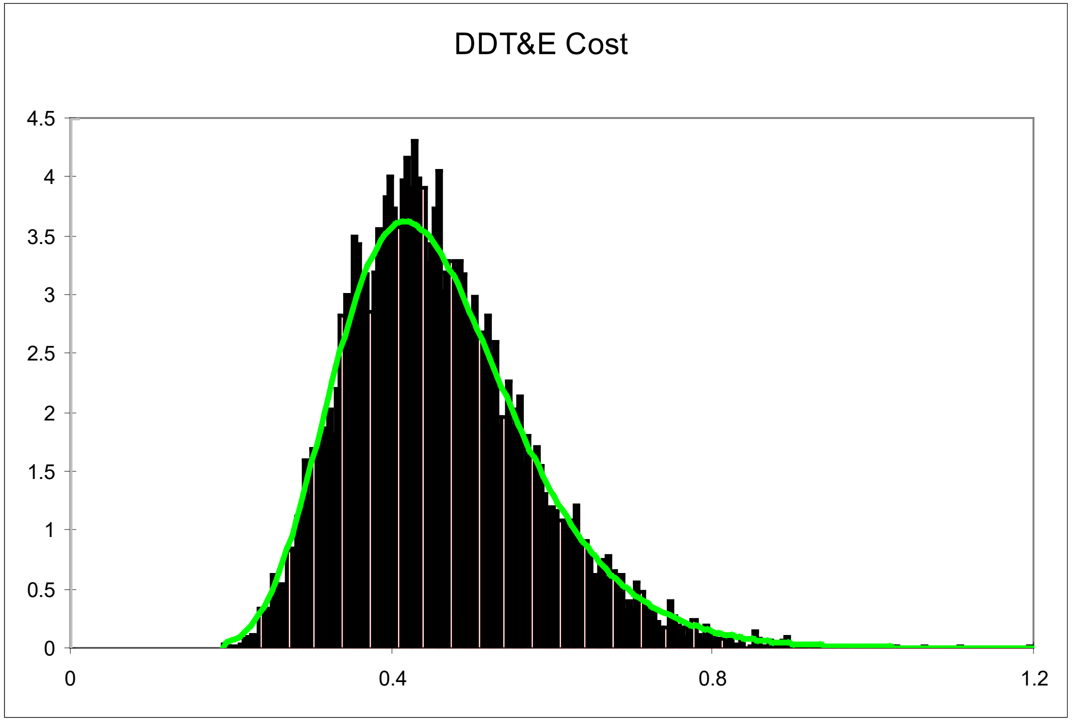
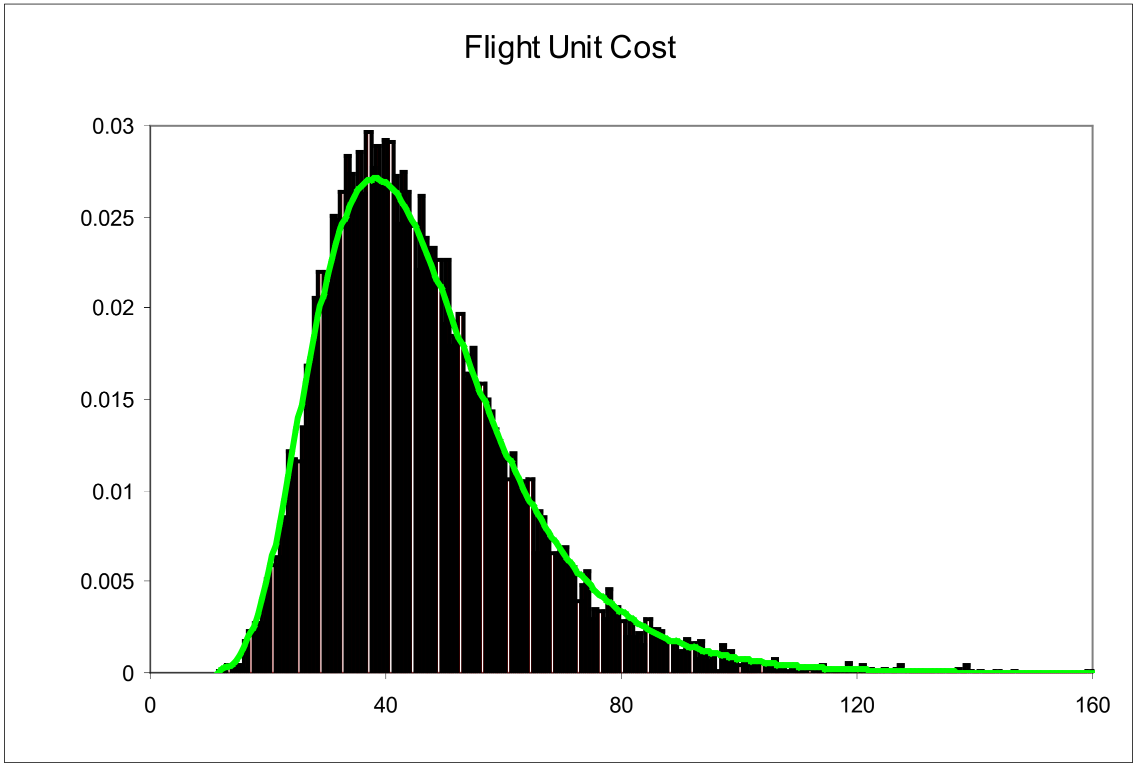
Test Case 1 Overlay Comparison – DDT&E*

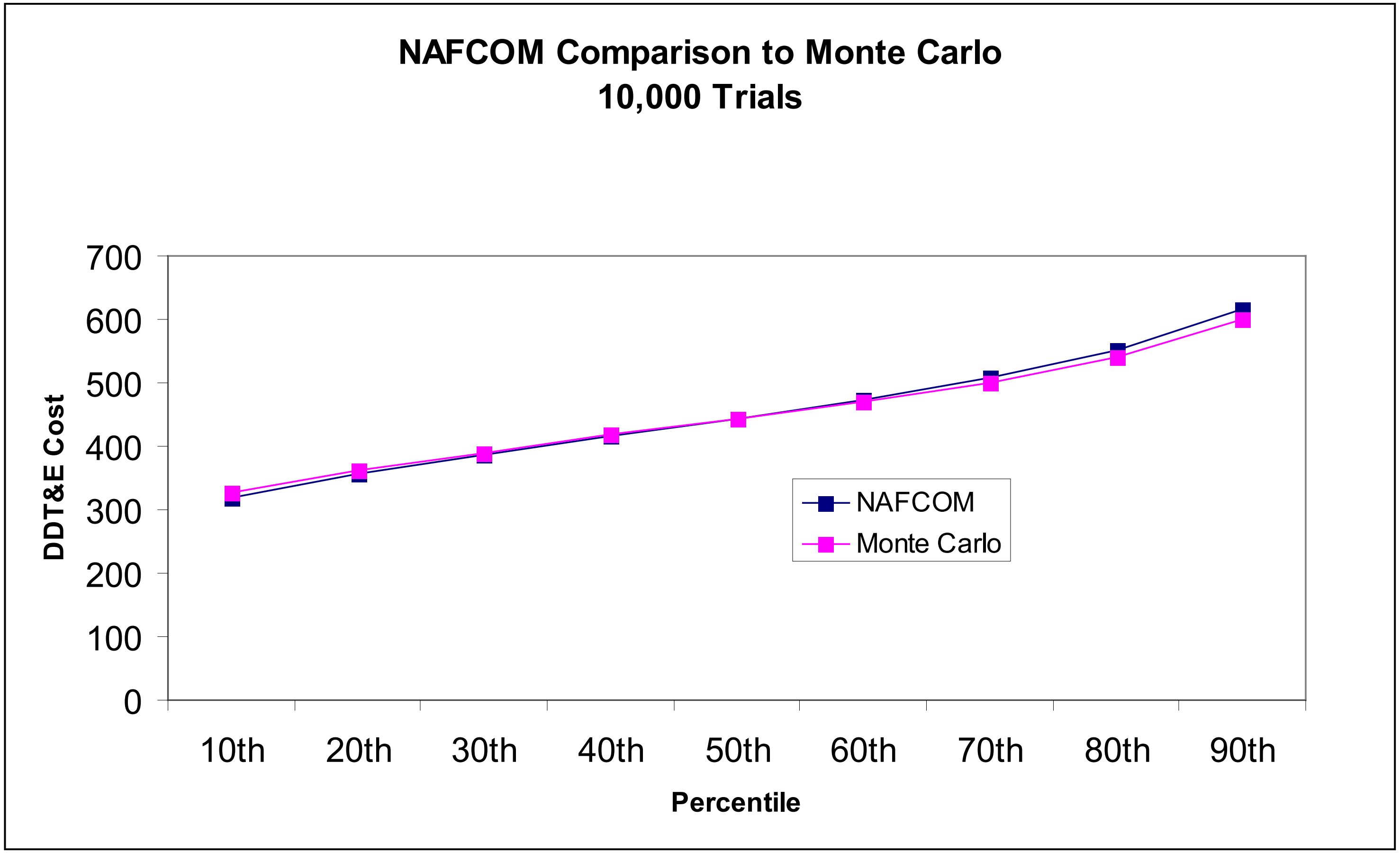


* The green line represents the Lognormal distribution from NAFCOM and the histogram represents the Monte Carlo simulation results.

Test Case 1 Overlay Comparison – Flight Unit



Test Case 1 DDT&E Percentile Comparisons



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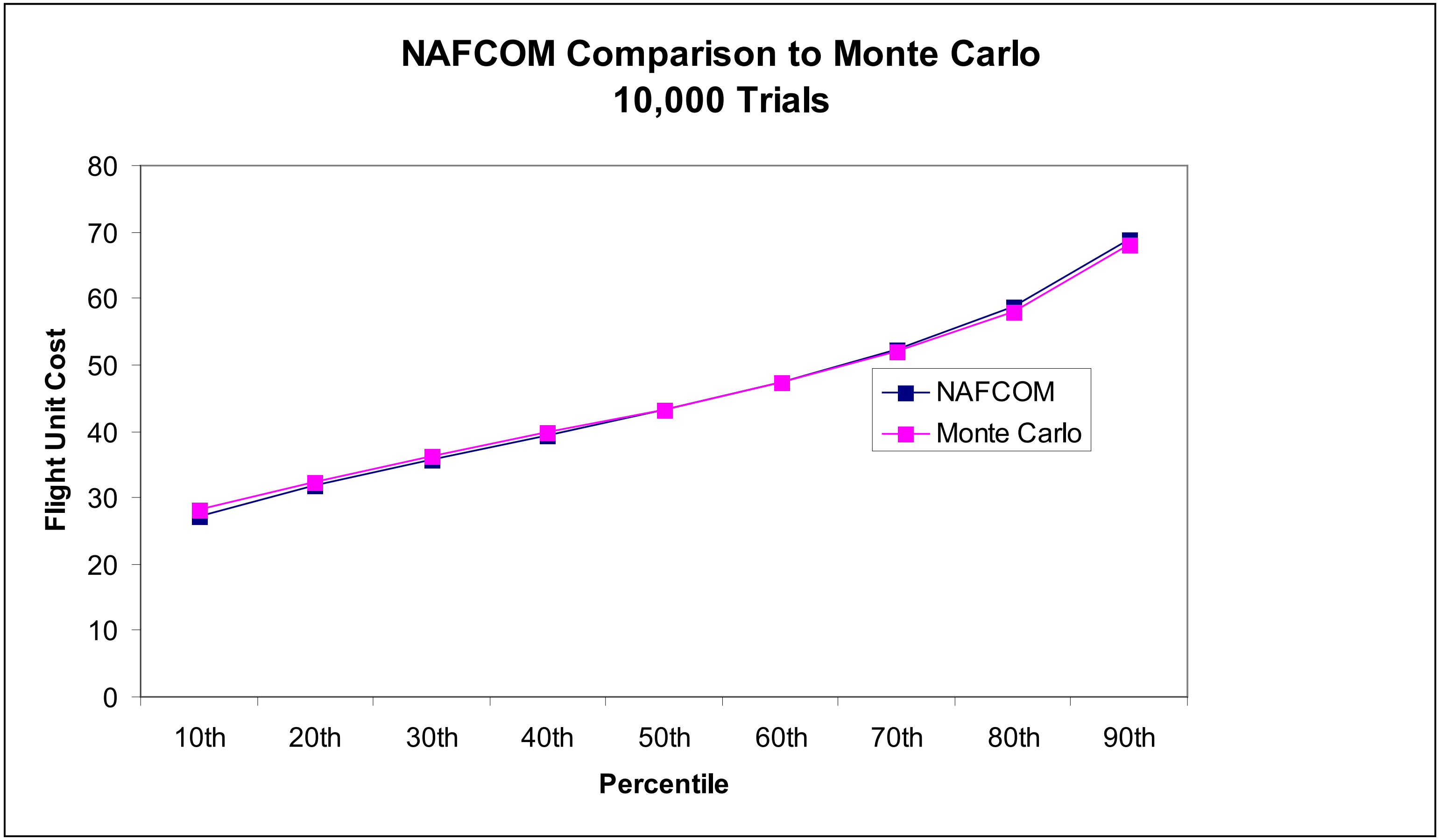
Test Case 1 Flight Unit Percentile Comparisons



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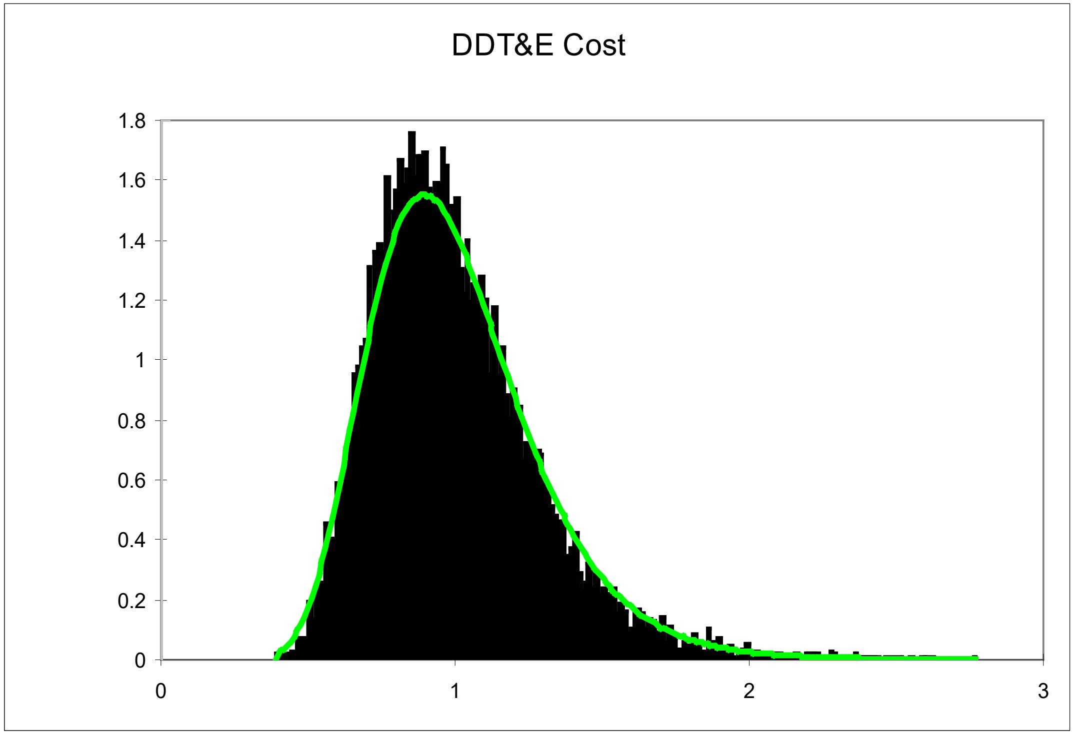
Test Case 2

- Consists of the same hardware subsystems as Test Case 1
- Also includes systems engineering

Test Case 2 DDT&E Overlay Comparisons



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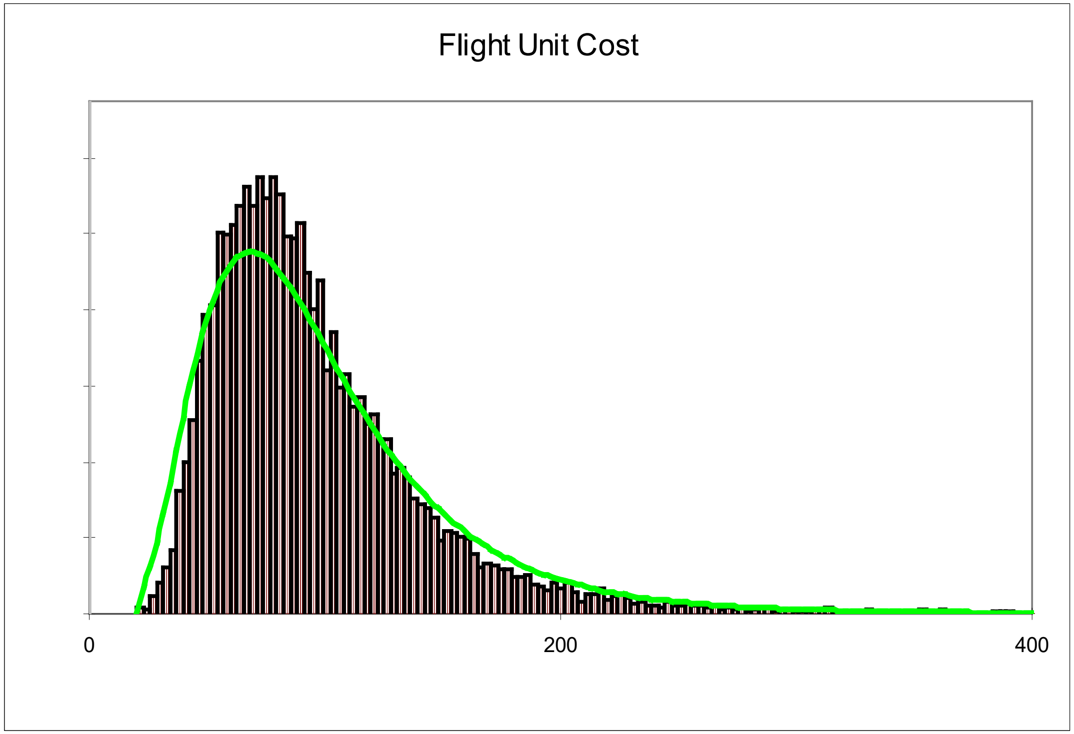
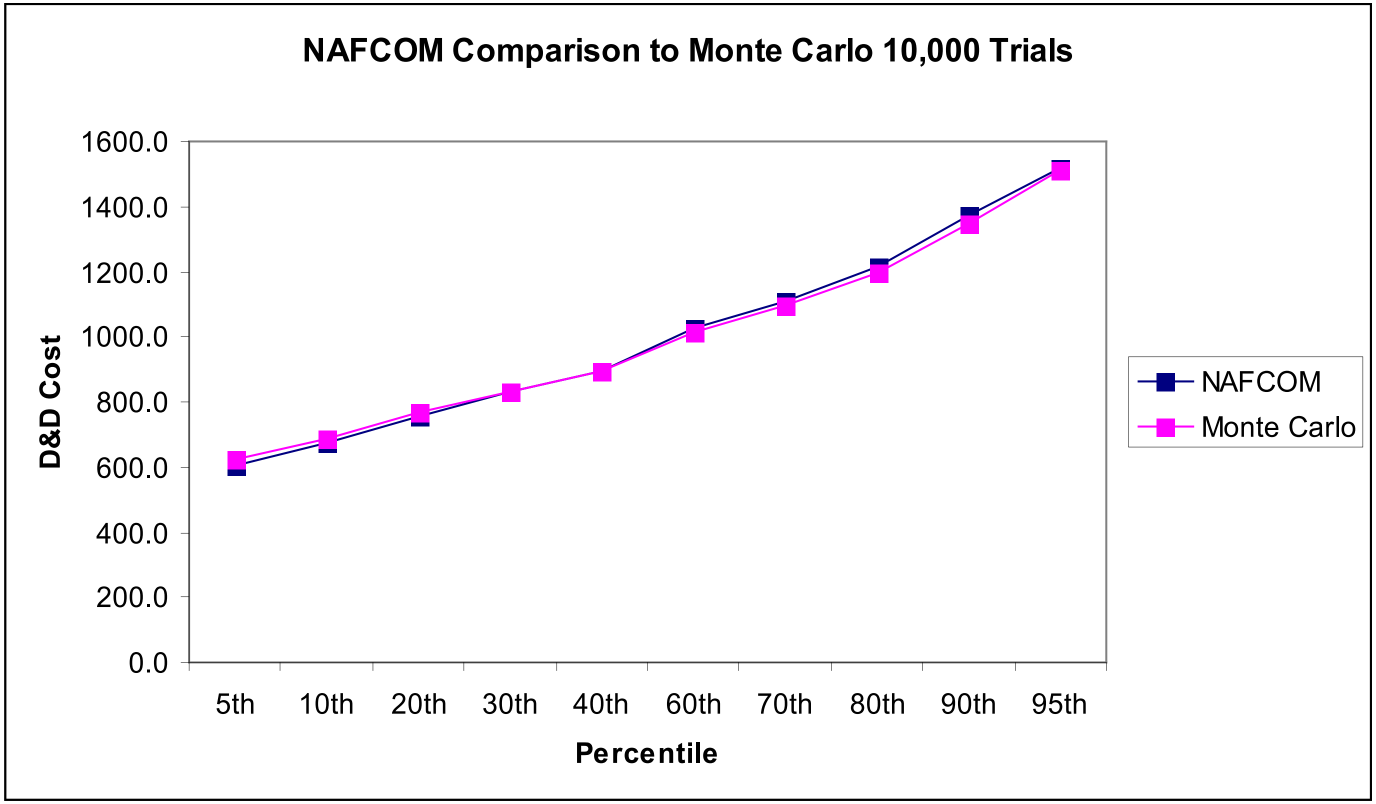
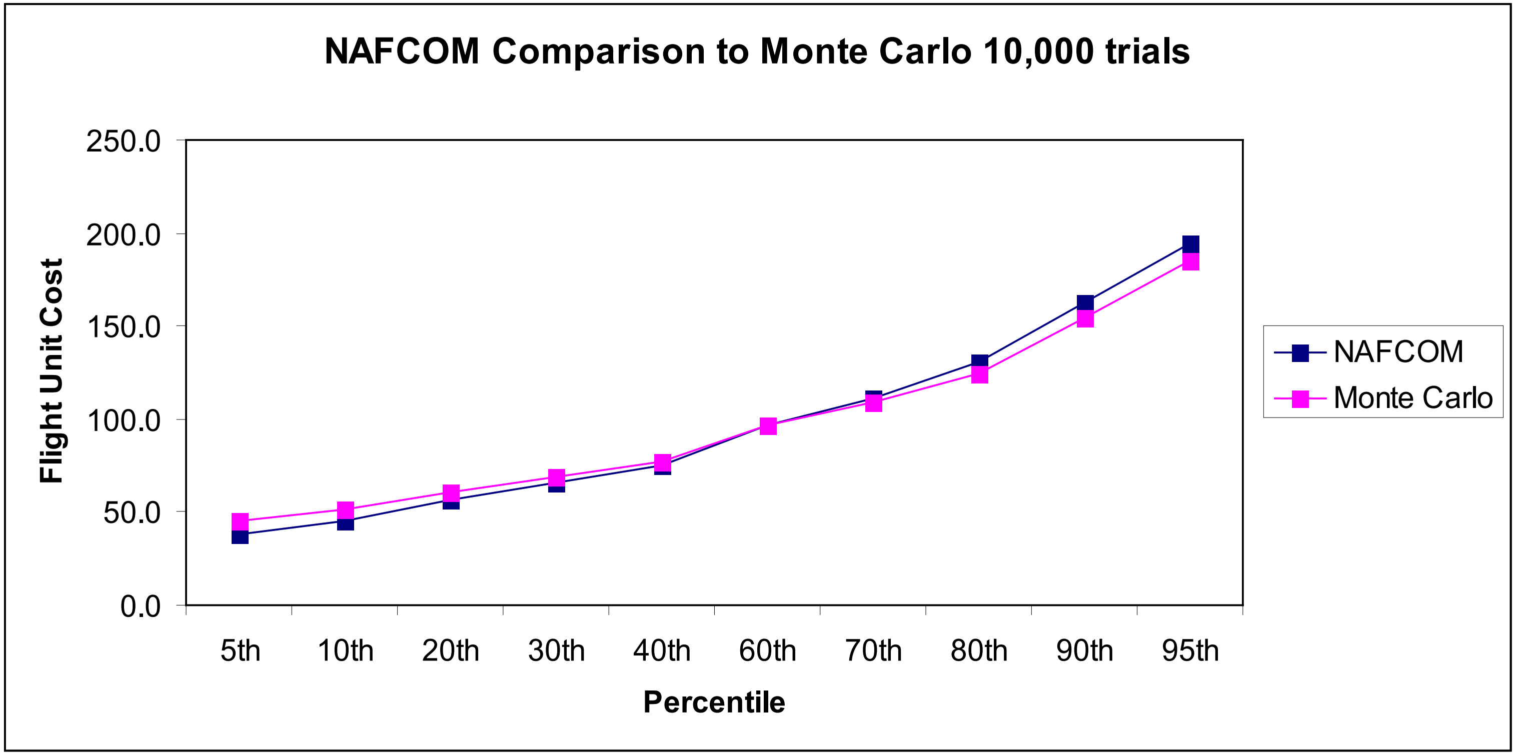
Test Case 2 Flt. Unit Overlay Comparisons



Test Case 2 DDT&E Percentile Comparisons



Test Case 2 Flight Unit Percentile Comparisons



Test Case 3

- Consists of a single stage vehicle, subsystem hardware plus systems engineering.
- The hardware elements include 7 subsystems
  - Structures
  - Thermal control
  - Electric power
  - Command control and data handling
  - Guidance navigation and control
  - Reaction control/auxiliary propulsion
  - Main propulsion (less engines) subsystems.

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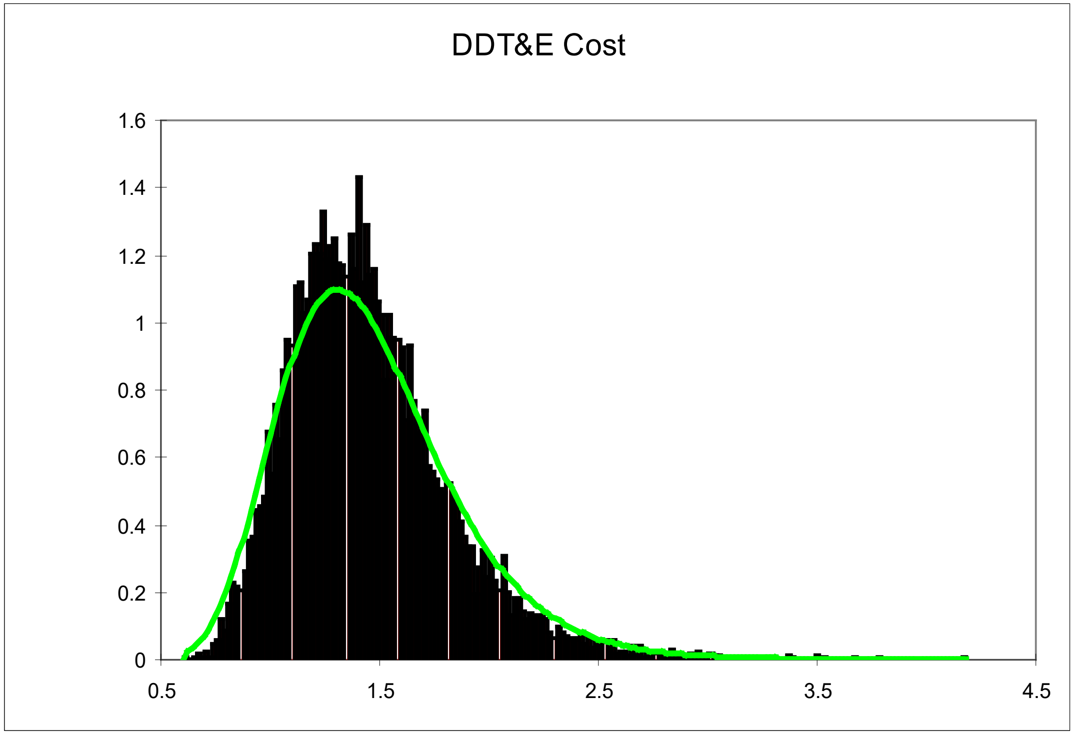
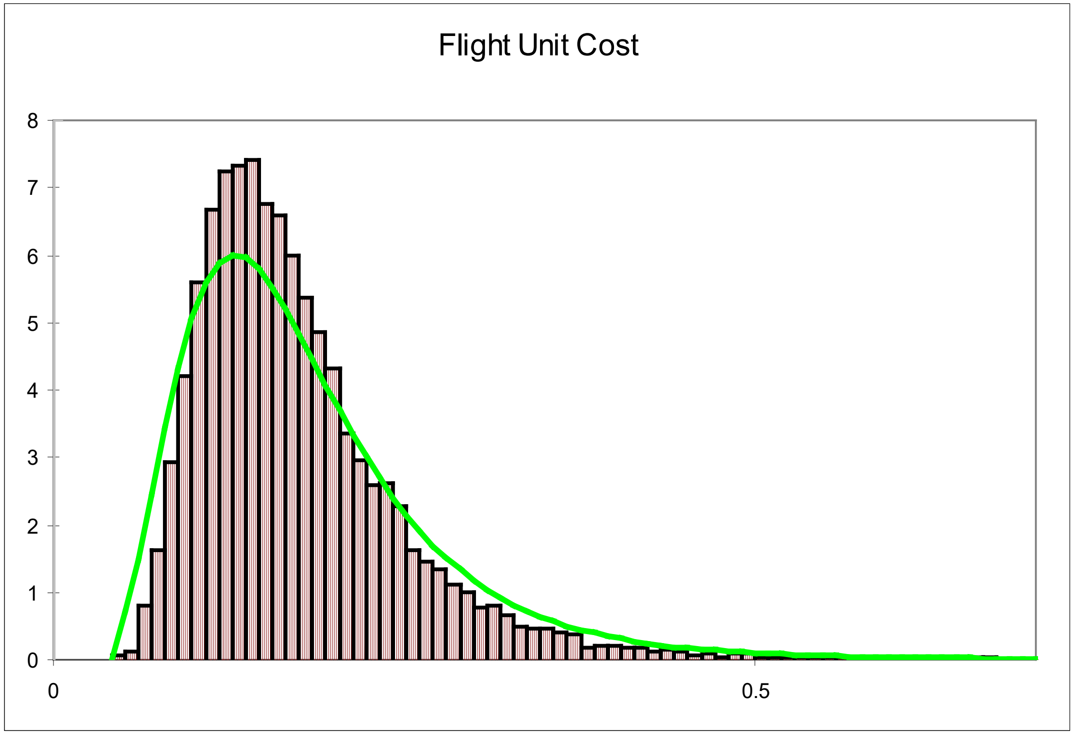
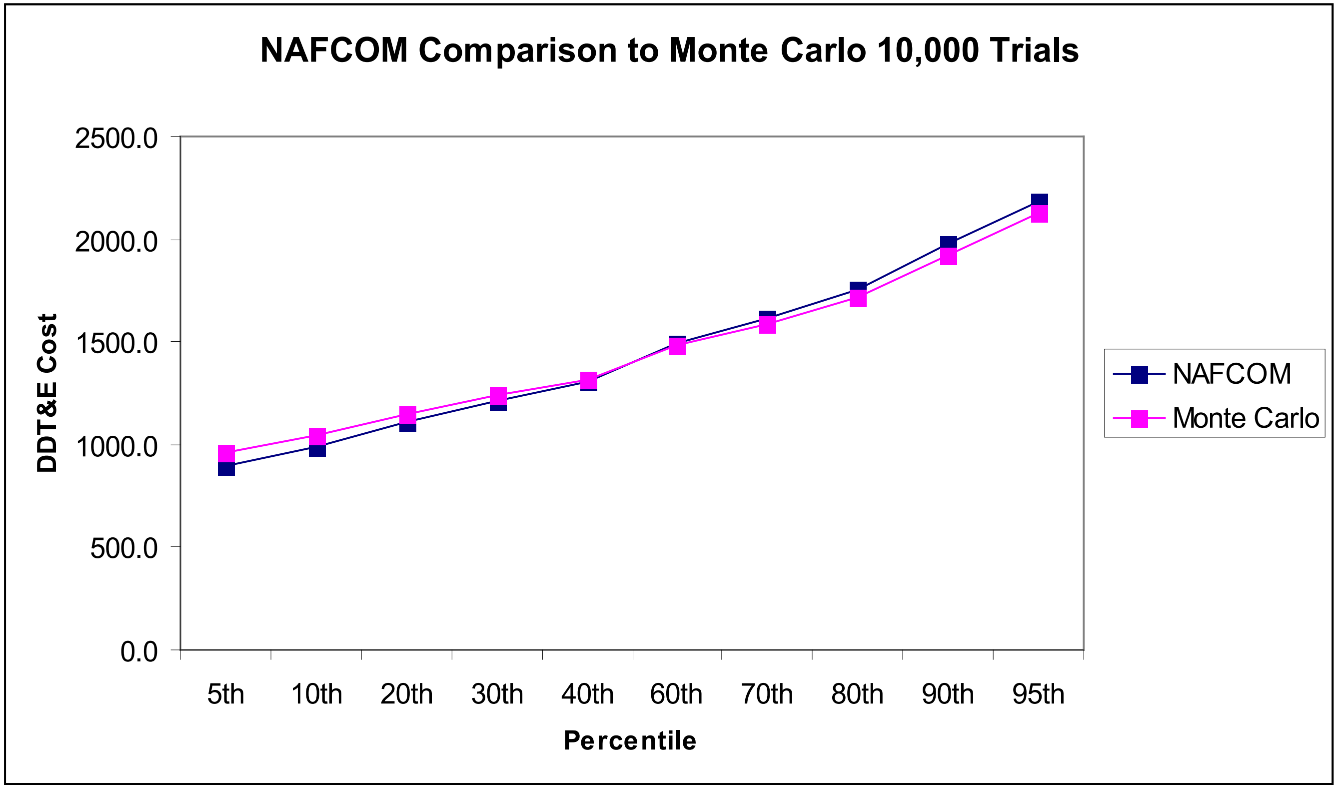
Test Case 3 DDT&E Overlay Comparisons



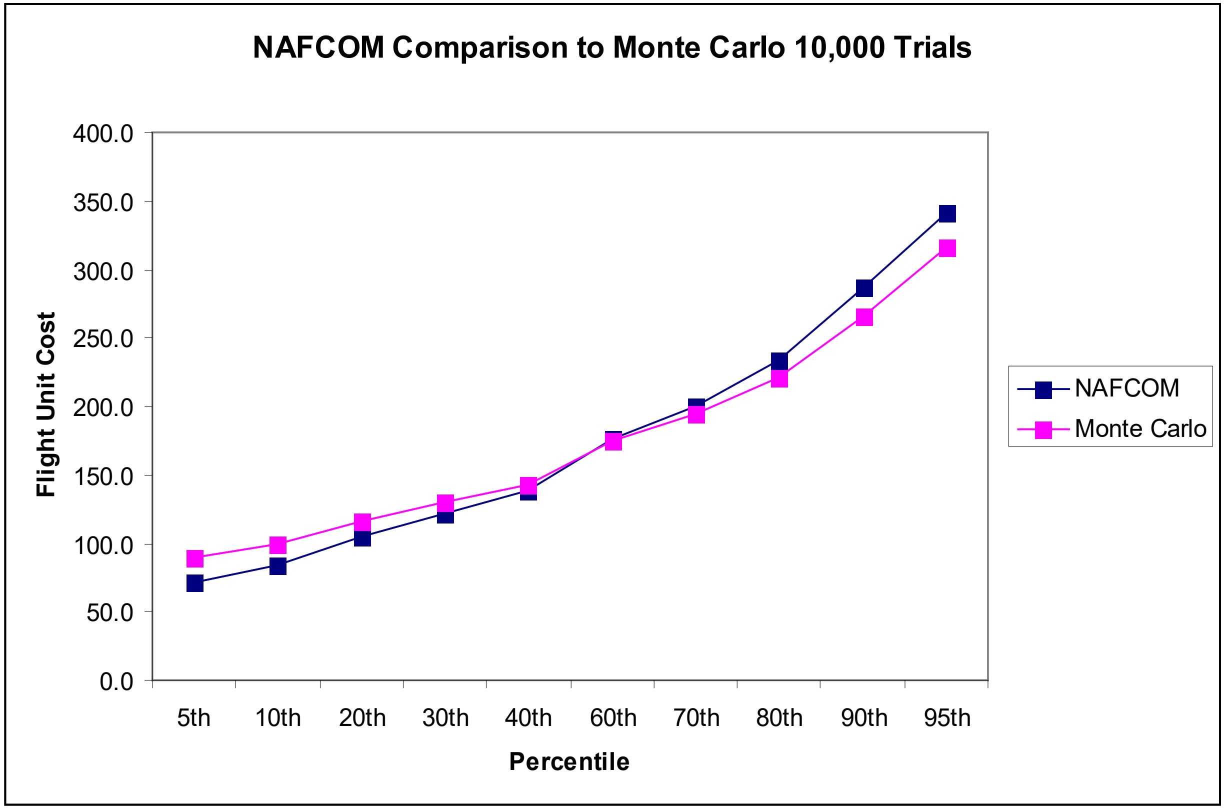
Test Case 3 Flight Unit Overlay Comparisons



Test Case 3 DDT&E Percentile Comparisons



Test Case 3 Flight Unit Percentile Comparisons



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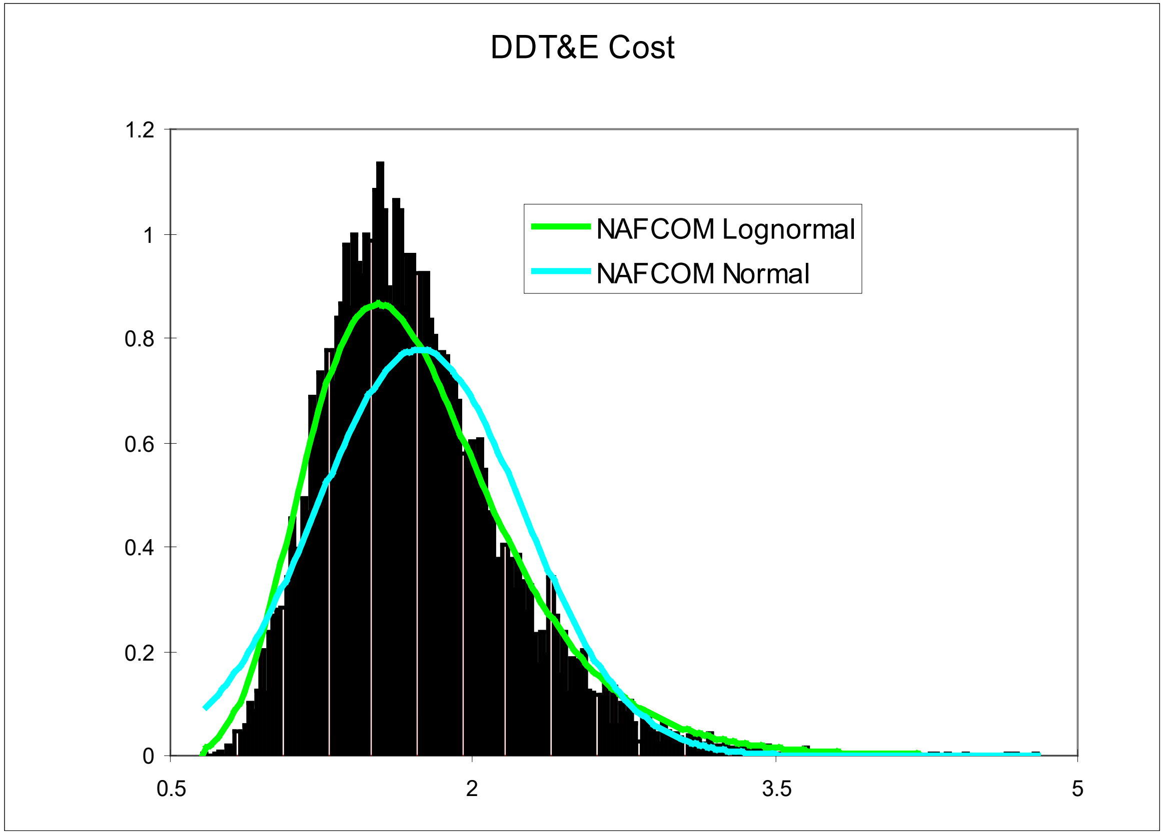
Test Case 4

- Consists of a single stage vehicle, subsystem hardware plus systems engineering
- The hardware elements are the same as for test case 3
- Test case 4 is similar to test case 3
  - The only difference is that the inputs vary more than in test case 3

Test Case 4 DDT&E Overlay Comparisons



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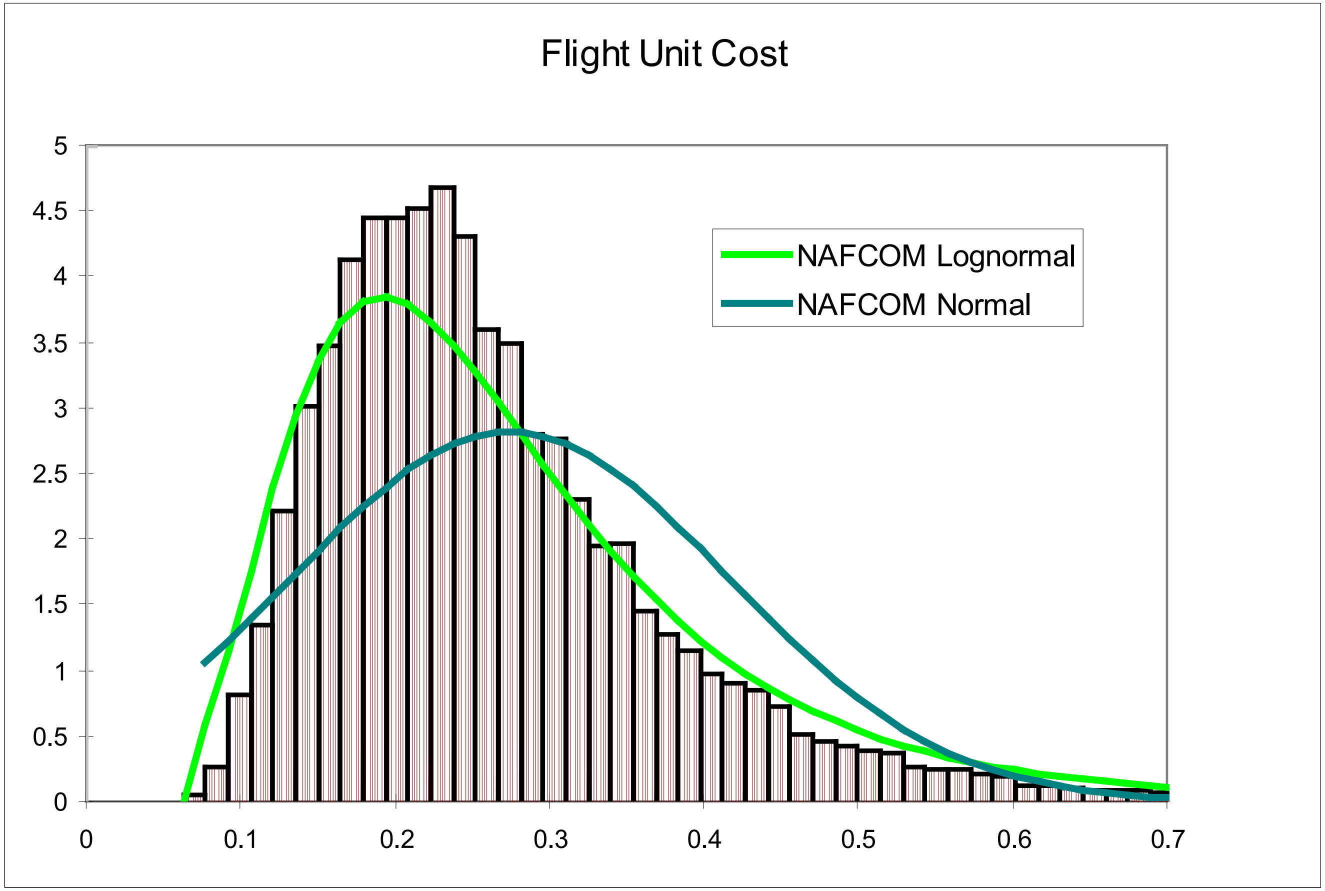
Test Case 4 Flight Unit Overlay Comparisons



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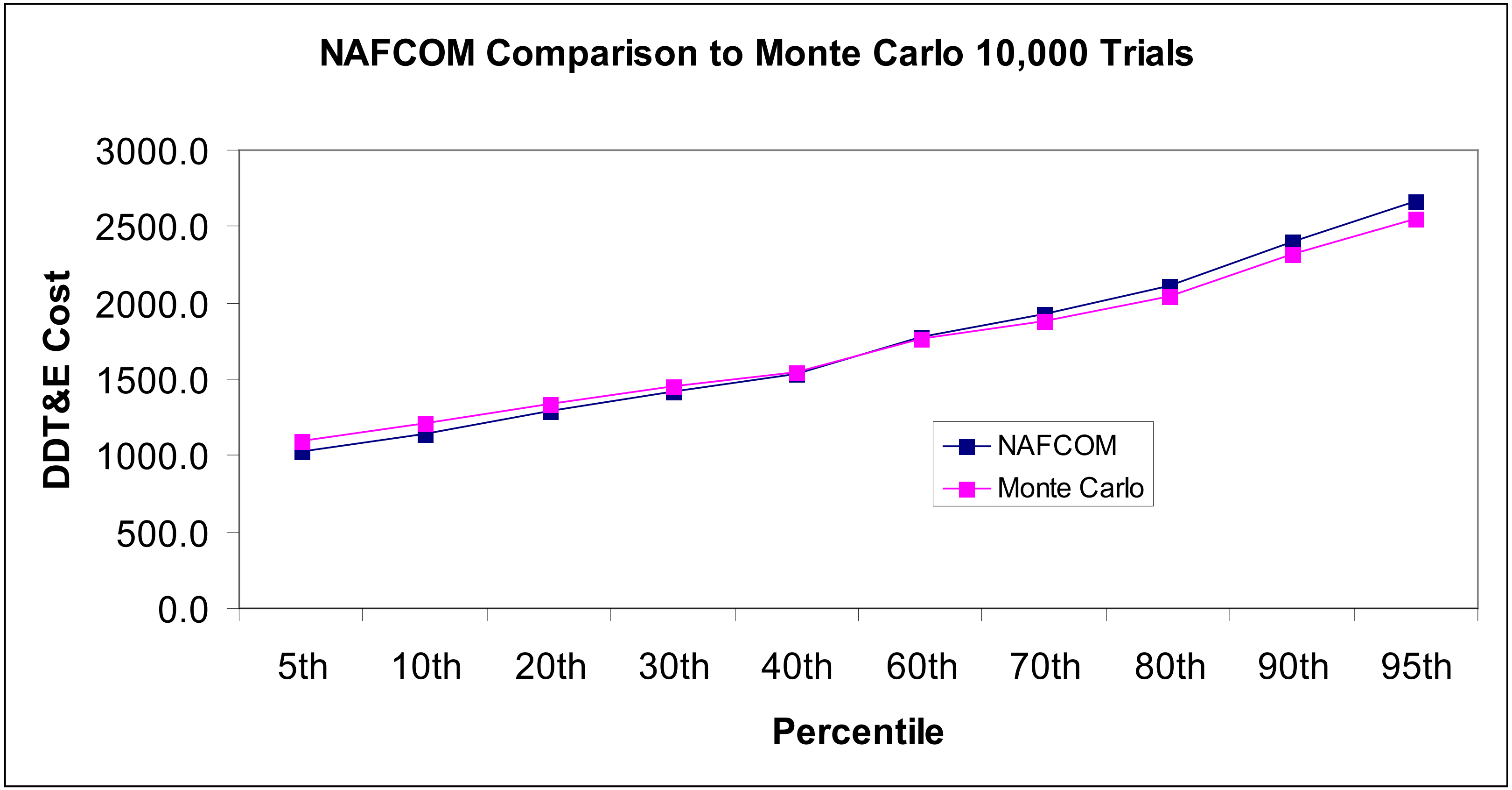
Test Case 4 DDT&E Percentile Comparisons



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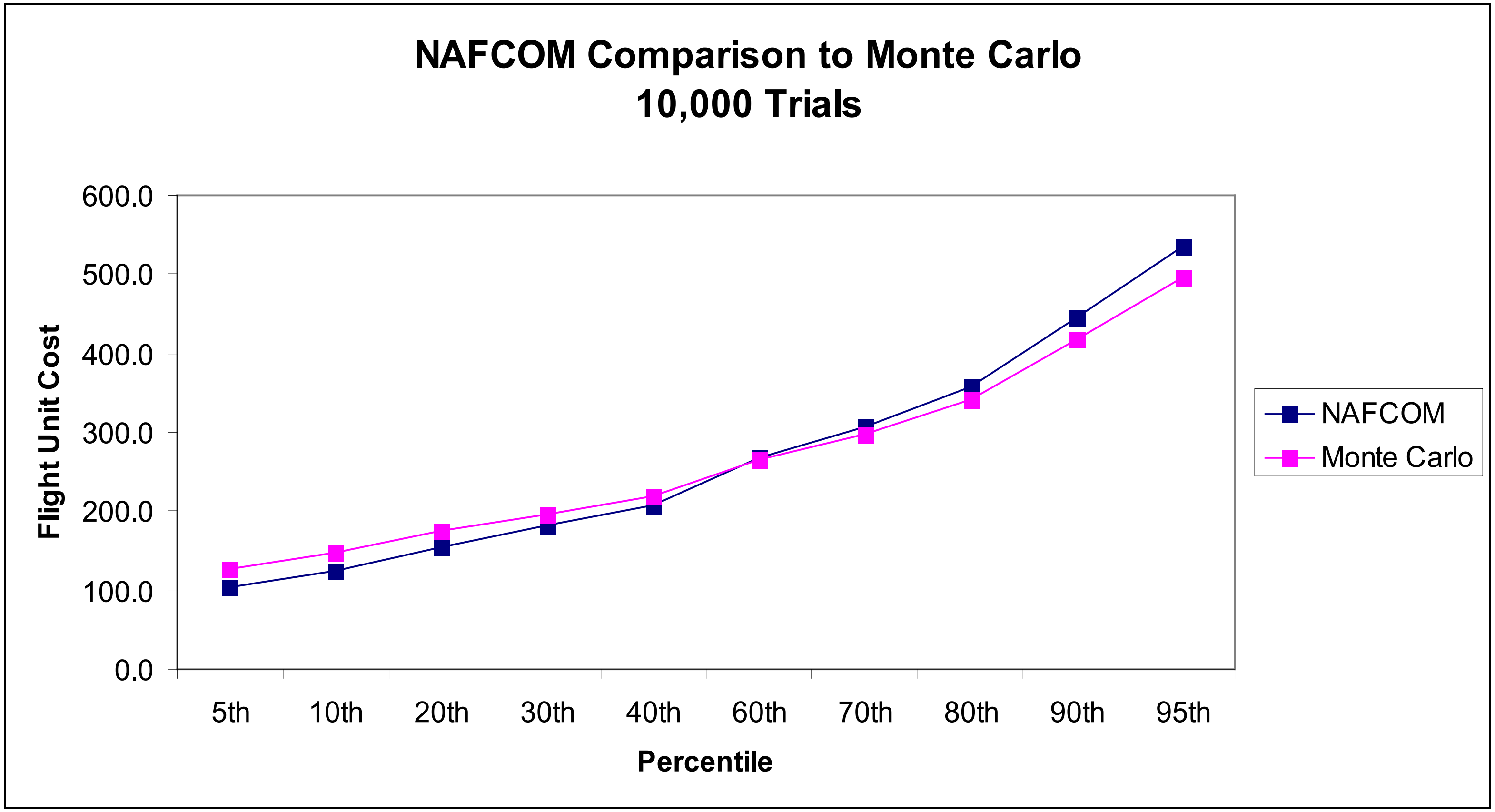
Test Case 4 Flight Unit Percentile Comparisons



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NAFCOM Risk Capabilities
Summary

- Uses well-documented analytical method to calculate risk
- User can input low, most likely, and high values for all NAFCOM complexity generator and conventional CER inputs
- Incorporates both technical and estimating uncertainties
- Incorporates correlation between subsystem costs
- Results displayed to the user are summary statistics, probability densities, and cumulative distributions for DDT&E, Flight Unit, Production, and Total Costs for each major estimating element (i.e. stage, bus, etc.)
- User can select either the Normal distribution or the Lognormal distribution to approximate the final results
- Provides similar results to Monte Carlo simulation

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