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Time–Phasing Methods and Metrics

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37th Annual DoD Cost Analysis Symposium
Williamsburg, VA
10-13 February 2004

This research was initiated by the Intelligence Community Cost Analysis Improvement Group (IC CAIG) and jointly sponsored by the National Reconnaissance Office Cost Group (NCG). Views expressed herein do not reflect the official policy or position of the IC CAIG, NCG, or the U.S. government.

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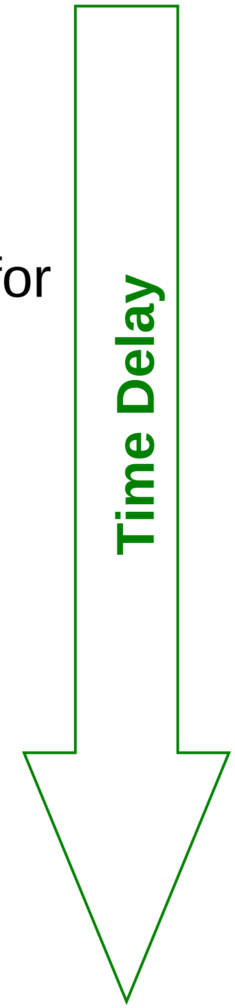
Contents

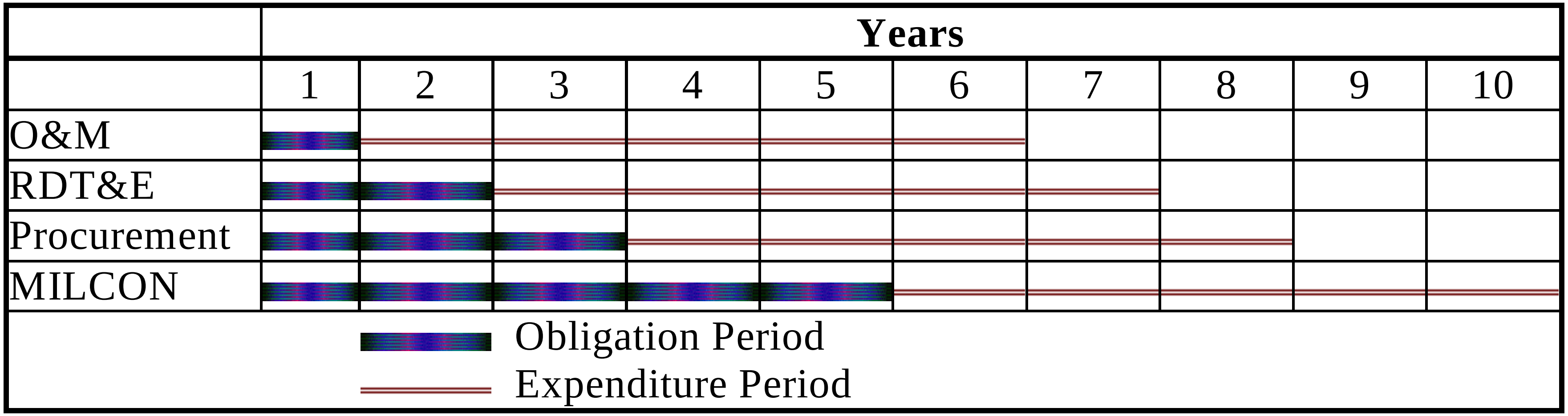
- Review
- Four common pitfalls
  - Lack of accuracy metrics
  - Trouble incorporating independent variables
  - Ambiguous start and end dates
  - Failure to convert cost to budget
- Space-system case study

Financial Management Terms That Matter

- ***Budget Authority:*** Authority by law to incur obligations
- ***Obligation Authority, Total Obligation Authority (TOA):*** Budget authority plus other funds available for obligation
- ***Obligations:*** Contract award
- ***Costs Incurred:*** Actual cost of work performed
- ***Expenditures:*** Sending the check
- ***Outlays:*** Cashing the check



Expenditures Lag Budgets by Years!



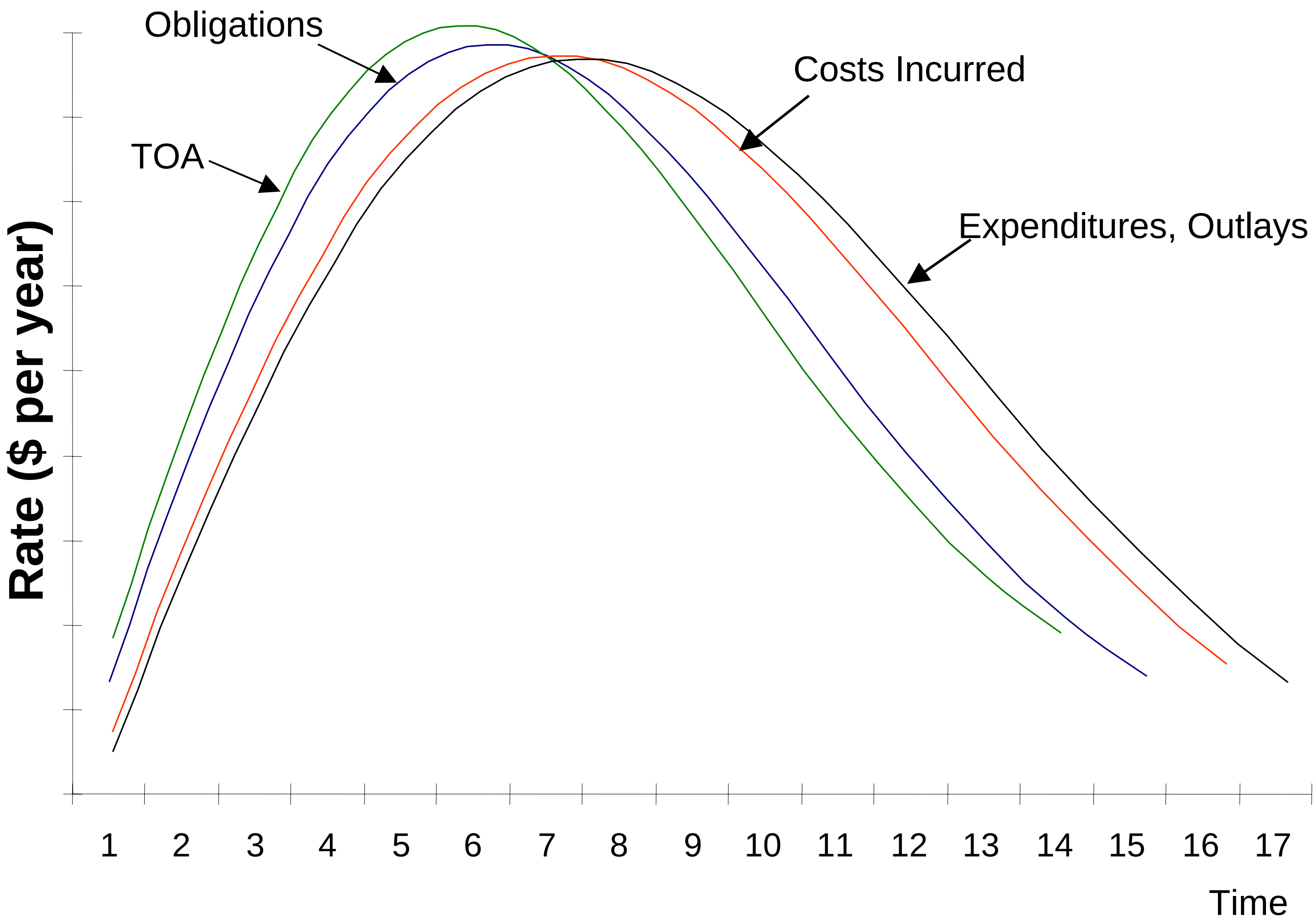
Source: DSMC (Tack 1997)

Example: Outlay Rates (% of Year-1 TOA expended)

	Year 1	Year 2	Year 3	Year 4	Year 5
AF RDT&E	60%	32%	4%	2%	2%

Source: USD(C). National Defense Budget Estimates for 2003: Green Book. March 2002.

Program has Multiple Time-Phased Profiles



High-Level Phasing Models

- Rayleigh distribution provides good fit for development programs (Abernathy 1984; Elrod 1993; Lee et al. 1993; Watkins 1982)

$$E(t) = d\left[1 - e^{-\alpha t^2}\right]$$

$\beta = 2$

$\alpha = 1/\delta^{\beta}$

$\gamma = 0$

- Weibull distribution is better

  (Brown et al. 2002; Porter 2001; Unger 2001)

$$E(t) = d\left[1 - e^{-\left(\frac{t-\gamma}{\delta}\right)^{\beta}}\right]$$

Rayleigh Model

- Underlying theory from Peter Norden (1970): Cumulative cost incurred, *E*(*t*), is product of two functions
  - Percent of work remaining
  - Linear increase in skills/knowledge acquired

- General form: $$E(t) = d\left(1 - e^{-\alpha t^2}\right)$$

- Infinite tail must be truncated, giving

$$d = D / E(t_c) = D / \left(1 - e^{-\alpha t_c^2}\right)$$

t_c = time of completion

$\boldsymbol{D}$ = total cost

- Parameter α determines time of peak expenditures (front/back loading)

How Much Front-Loading?

- Gallagher and Lee (1996) propose to fix completion time as when 97% of total funds are expended
  - Results in peak expenditures at 38% complete
  - Results in 60% spent at 50% time (a.k.a. 60/50 Rayleigh)
  - Truncation and resulting fixed Rayleigh now often referred to as "convention"
  - Rayleigh often mischaracterized as having fixed time of peak expenditures (not true)
- Case study of 14 single-satellite contracts gives average of 59% spent at 50% time
- Earlier study of 69 Air Force programs (ESC 1995) gives average of 64% spent at 50% time

60/50 Rayleigh Appears Appropriate
When Commodity-Specific Models not Available

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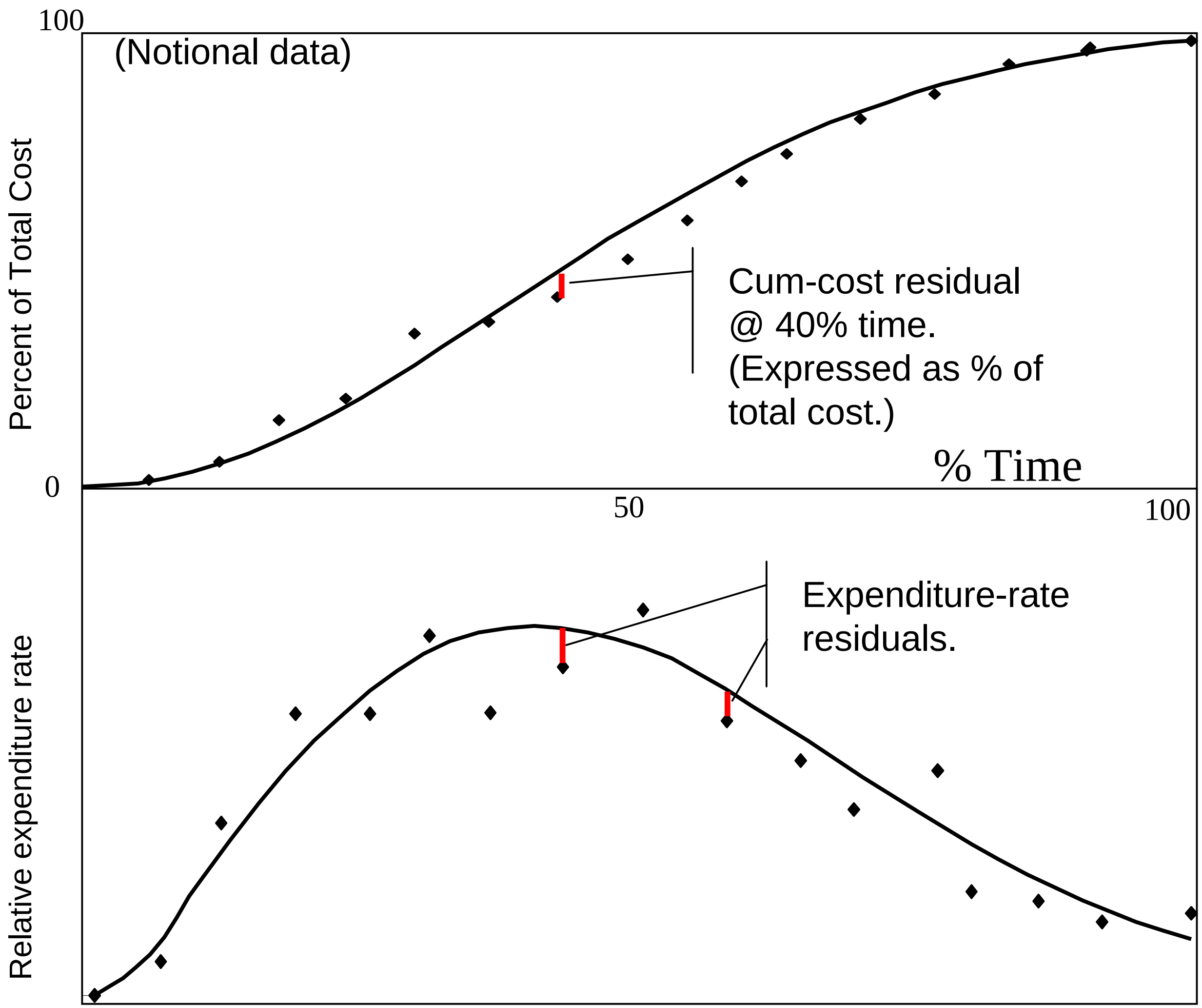
Need for Accuracy Metrics

- Predictive accuracy metrics needed
  - To compare models
  - To communicate with budget analysts
- Goodness-of-fit statistics often reported
  - Specific curves against individual programs
  - Not useful as predictive metric
- Metrics should be:
  - Based on actual vs. estimated costs
  - Independent of functional form (e.g., Weibull)
  - Independent of regression approach

Cumulative Costs, Spend Rates



Cum-cost data:

As reported by contractor

Basis for regressions

Used for 2 metrics:

1. ***Std. dev. of all cum-cost residuals***
2. ***Std. dev. of cum-cost residuals @ 40% complete***

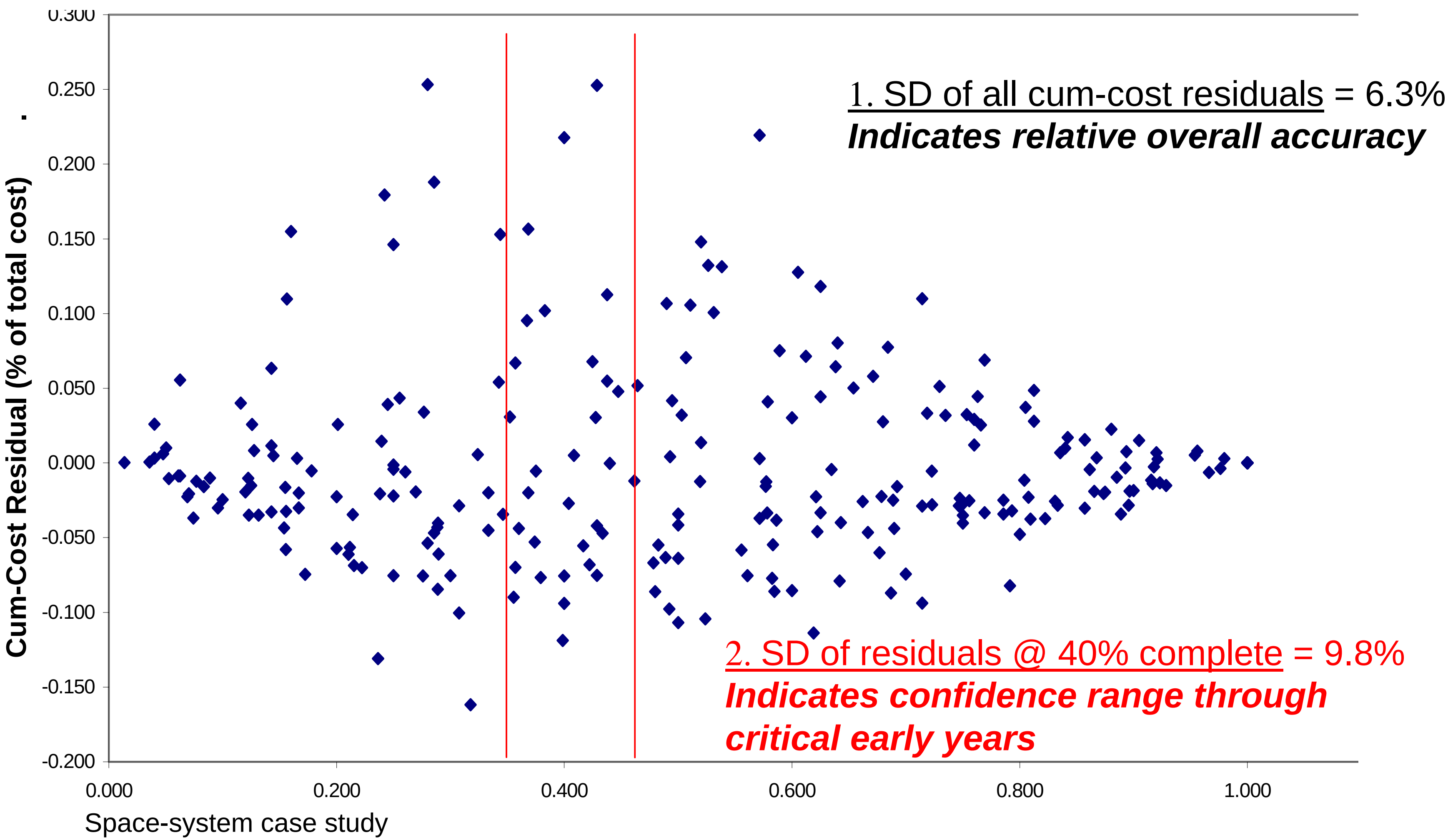
Expenditure-rate data:

Derived from cum-cost data

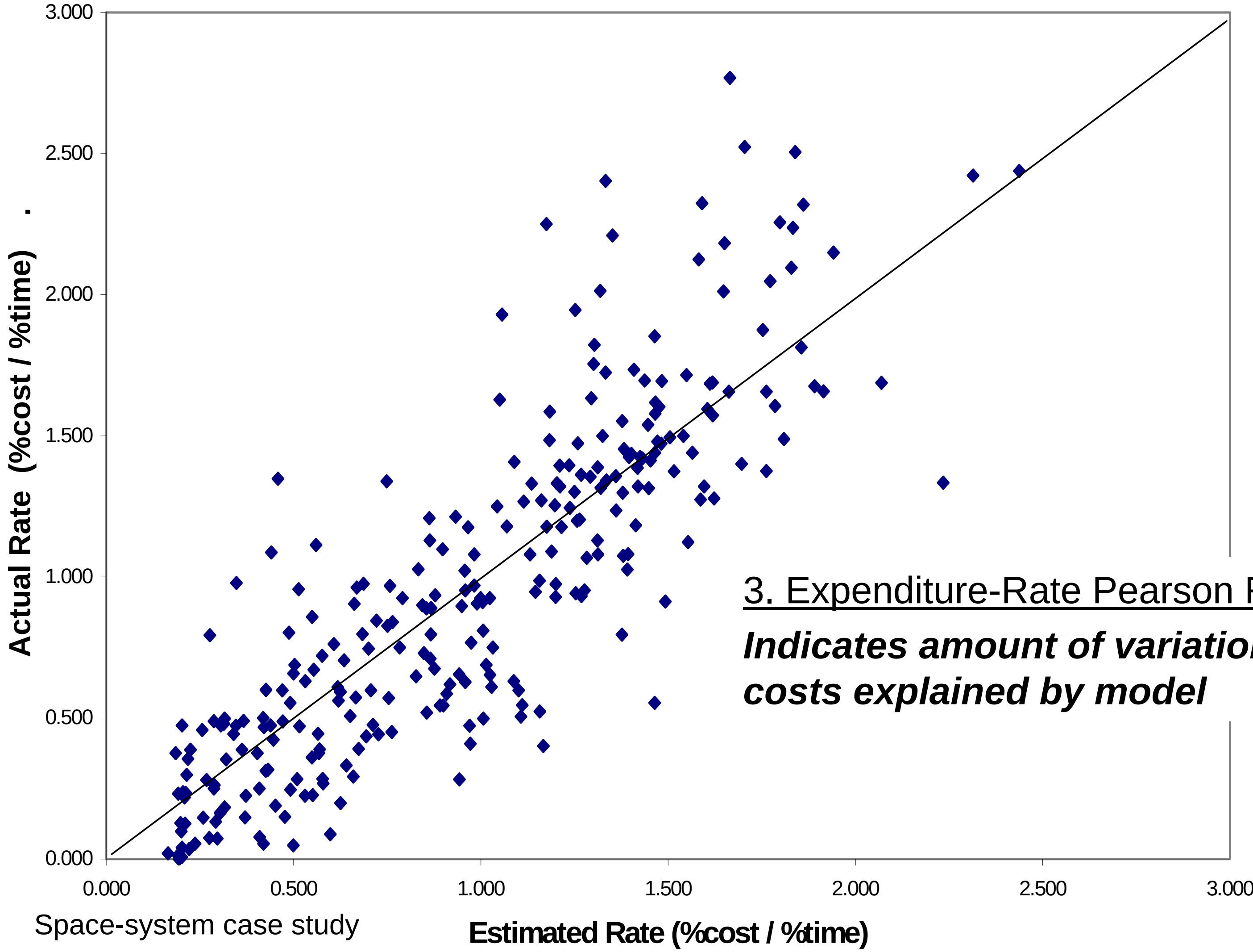
Used for 2 metrics:

3. ***Coefficient of Variation***
4. ***Pearson's R^2***

Metrics #1, #2


0.300
0.250
0.200
0.150
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
Cum-Cost Residual (% of total cost)
0.000
0.200
0.400
0.600
0.800
1.000
Space-system case study
1. SD of all cum-cost residuals = 6.3%
Indicates relative overall accuracy
2. SD of residuals @ 40% complete = 9.8%
Indicates confidence range through critical early years

Metric #3: Pearson R^2 of Actual vs. Estimated Rate

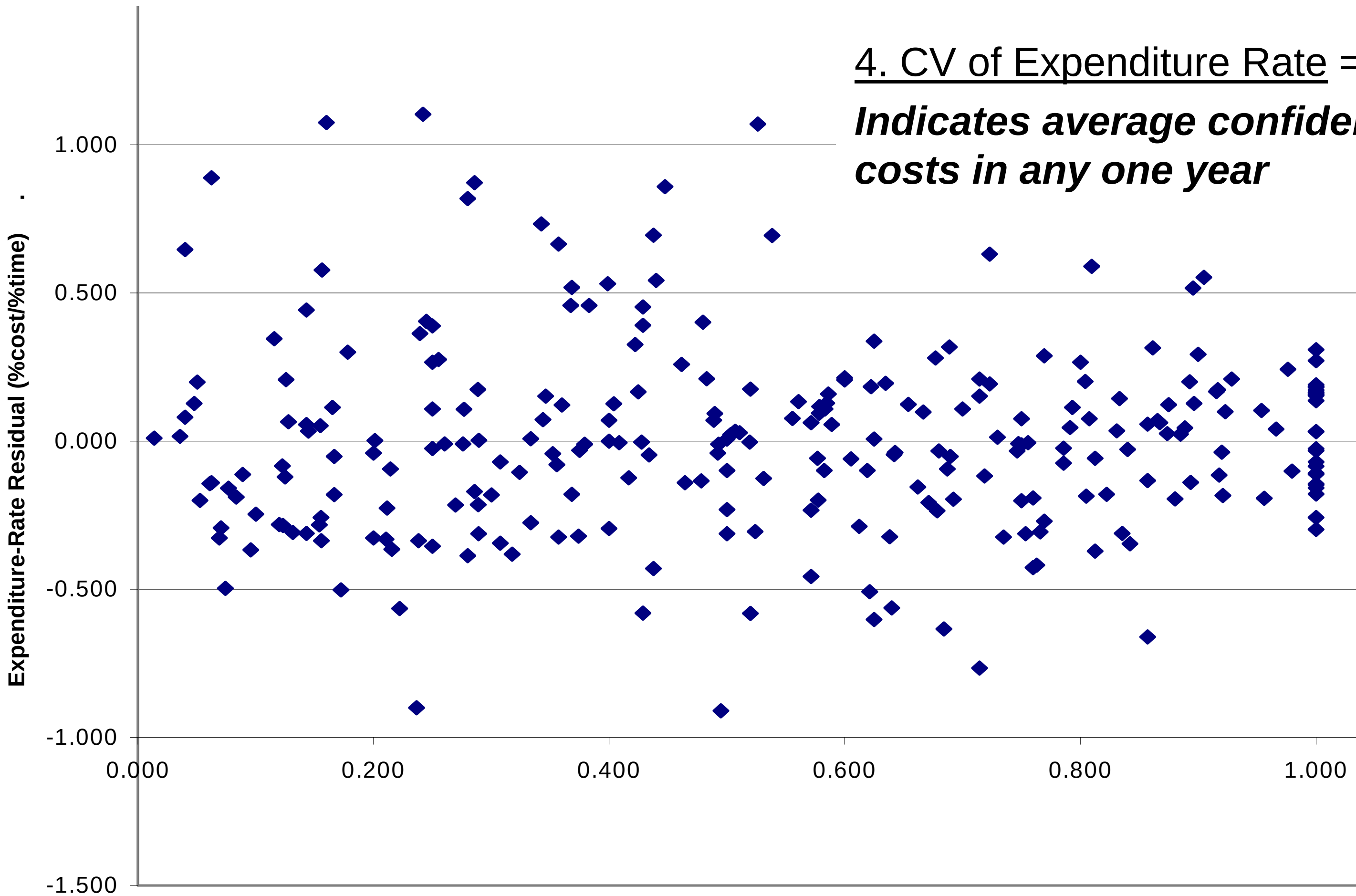


3. Expenditure-Rate Pearson R^2 = 0.73

Indicates amount of variation in annual costs explained by model

Space-system case study

Metric #4:
Expenditure-Rate Coefficient of Variation



4. CV of Expenditure Rate = 32%

Indicates average confidence range of costs in any one year

Space-system case study

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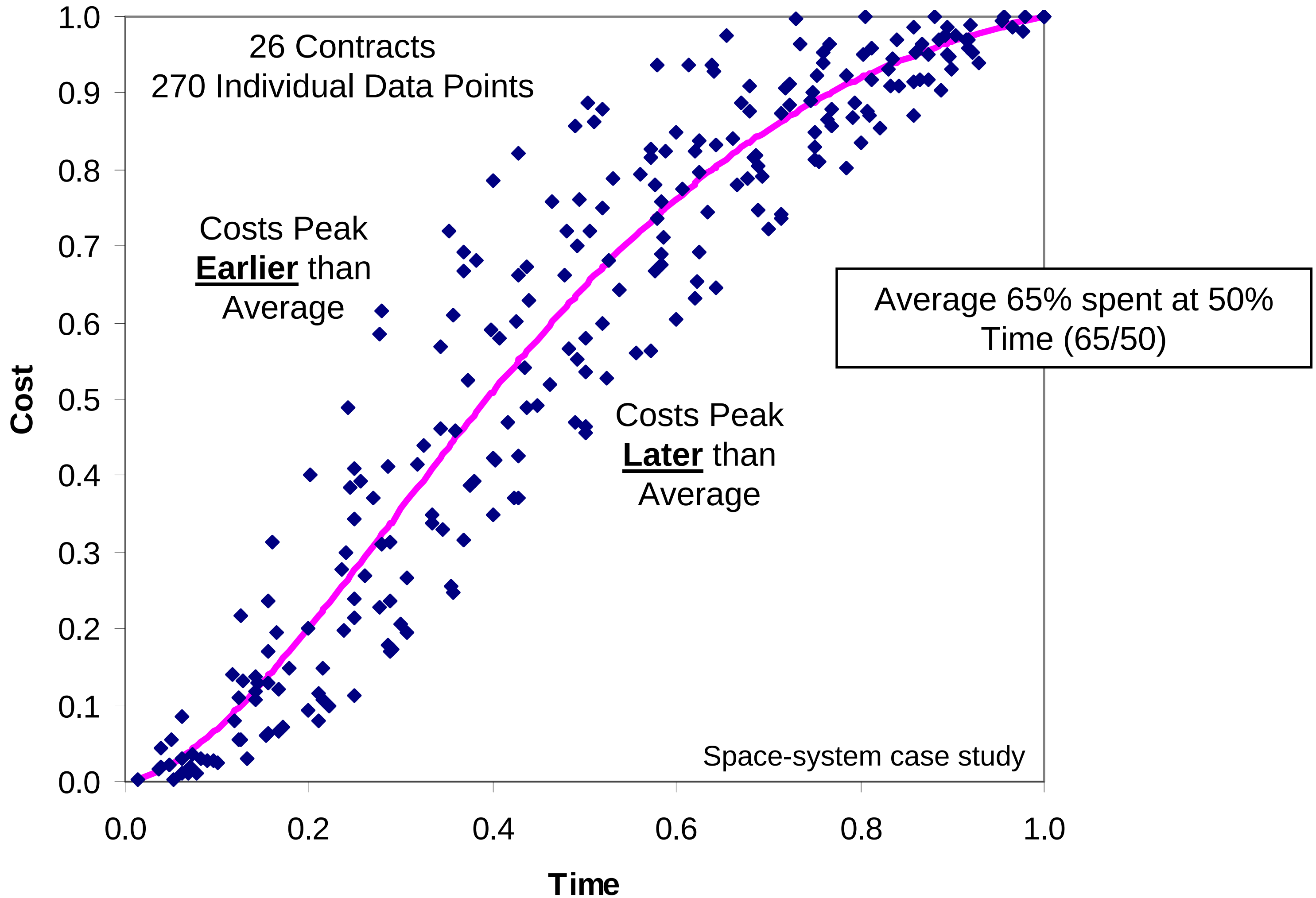
All Data: Cumulative Cost vs. Time



Modeling Objective: Improve Accuracy using Explanatory Variables

Results: Simple Curves

Method	Result	SD of Cum. Residuals*	SD of Cum. at 40% complete	Pearson R^2 of Exp. Rate	CV of Exp. Rate
Single Rayleigh Distribution	alpha = 4.17	9.6%	15.0%	0.55	44%
Single Weibull Distribution	alpha = 2.97 beta = 1.64	9.2%	14.5%	0.58	40%
Single Beta Distribution	alpha = 1.46 beta = 2.04	9.6%	14.7%	0.49	44%

Space-system case study

- Single curves can be fit to aggregation of all data (no independent variables)
- Shows no significant difference among curve forms
- Provides baseline for improvement
- Not a bad model

* Curve fit minimizes this parameter

Adding Drivers: Multi-Stage Regression

***j* = 26 profiles with *i* data points each**
%cost, E_i vs. %time, t_i

STAGE 1

Run 26 regressions to estimate 26 pairs of parameters α, β

STAGE 2

Run one regression to estimate a, b, c

STAGE 3

Run one regression to estimate d, e, f

Minimizing

$$E(\alpha_j,\beta_j)=\sum_i\left(\frac{1-e^{-\alpha_j t_i^{\beta_j}}}{1\text{-}e^{-\alpha_j}}-E(t_i)\right)^2$$

Results in *j* sets of parameters α, β

Minimizing

$$\alpha(\mathrm{a,b,c})=\sum_j\left(\mathrm{a}+\mathrm{b}(Duration_j)+\mathrm{c}(\%NR_j)-\alpha_j\right)^2$$

$$\beta(\mathrm{d,e,f})=\sum_j\left(\mathrm{d}+\mathrm{e}(Duration_j)+\mathrm{f}(\%NR_j)-\beta_j\right)^2$$

Multi-Stage Regression Shortfalls

- Final model is not based on minimizing cost errors
- Parameters α, β estimated independently

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Adding Drivers: Single-Stage Regression

j = 26 profiles with i data points each
270 total data points (i*j)
%cost, $E_{i,j}$ vs. %time, $t_{i,j}$

Run one regression to estimate a, b, c, d, e, f

Minimizing

$$E(a,b,c,d,e,f) = \sum_{i,j}\left(\frac{1-e^{-\alpha t_i^{\beta}}}{1-e^{-\alpha}} - E(t_{i,j})\right)^2,$$

where

$$\alpha = a + b * duration_j + c * \%NR_j$$

$$\beta = d + e * duration_j + f * \%NR_j$$

Single-Stage Regression is More Accurate

- Directly minimizes cost errors
- Parameters α, β estimated simultaneously

Single vs. Multi-Stage Results

Method	Result	SD of Cum. Residuals	SD of Cum. at 40% complete	Pearson R^2 of Exp. Rate	CV of Exp. Rate
Weibull Model (Single-stage Regression)	α, β = f(%NR, Duration, #units)	6.3%	9.9%	0.72	33%
Weibull Model (Multi-stage Regression)	α, β = f(%NR, Duration, #units)	7.4%	11.9%	0.68	35%

Space-system case study

Single-stage results are better in all four metrics

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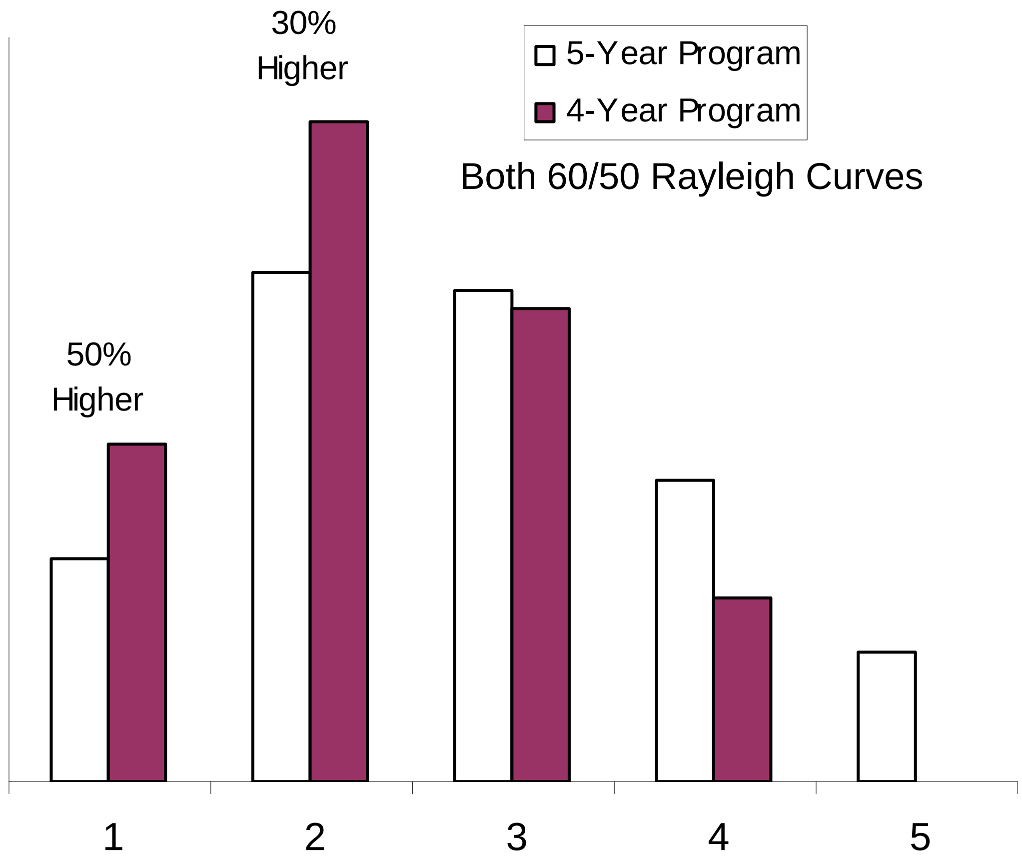
Defining Start, End Dates

- Must have precise definitions
  - Indexed to programmatic events
  - Common definition across programs, contractors

GOOD	**WORSE**
Contract Award Launch	PDR, CDR IOC, FOC Milestone B

- Ambiguous definition of "time" results in baseless accuracy metrics

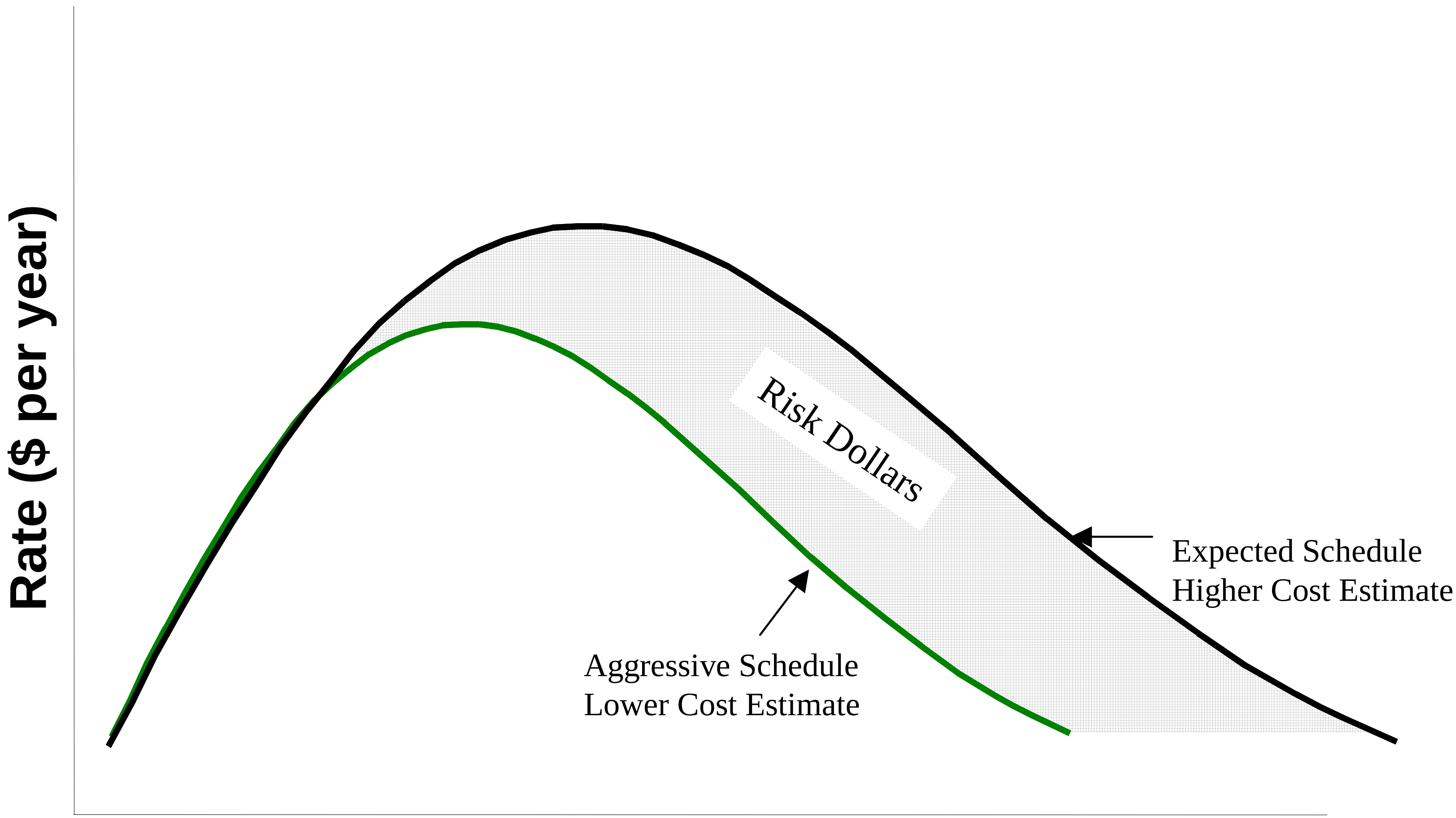
Need for Independent Schedule Estimate



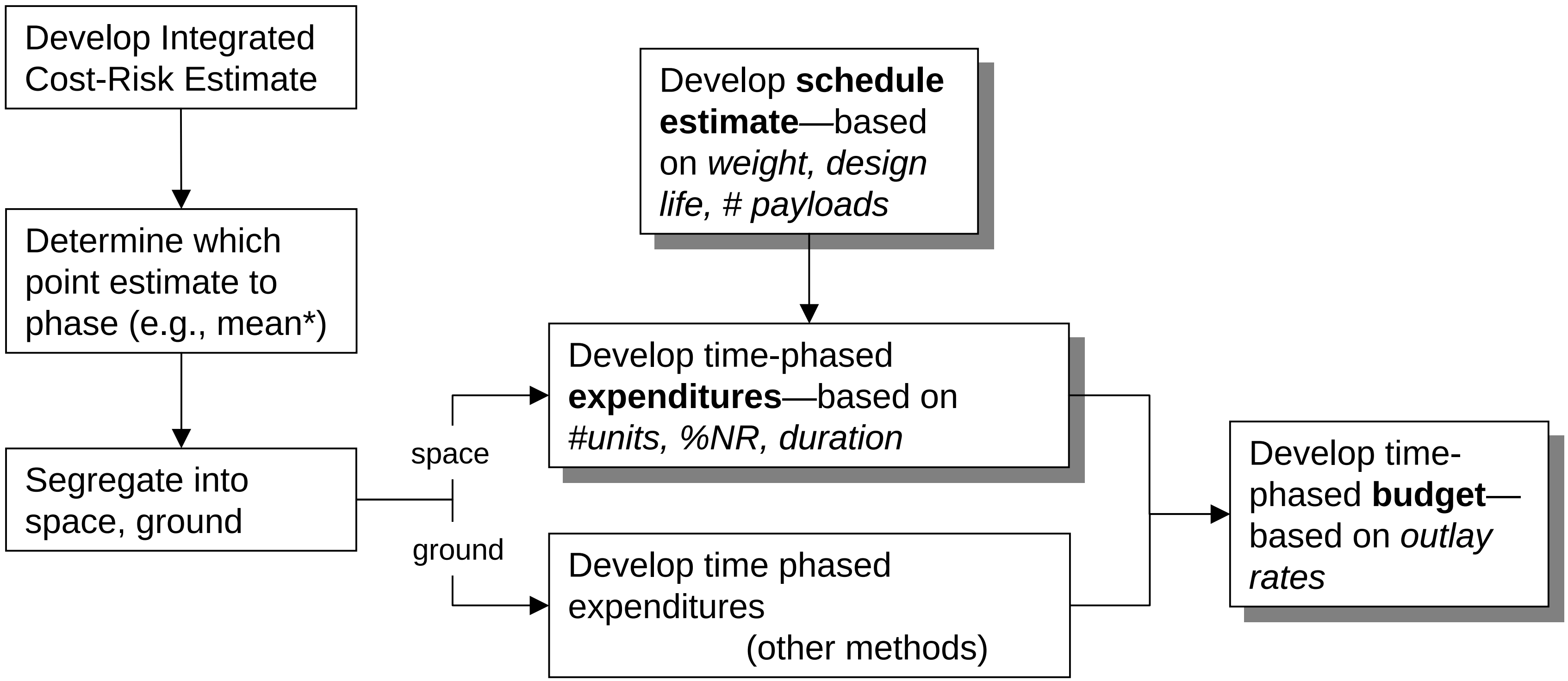
Don't phase costs to PM's optimistic schedule

- Small difference requires large funding increase in early years
- Even worse if ICE is higher than PM estimate

Integrated Cost, Schedule, Phasing Result



Integrated Time-Phasing Process



*May require fancy math if it's anything other than the mean

Contents

Converting Cost to Budget

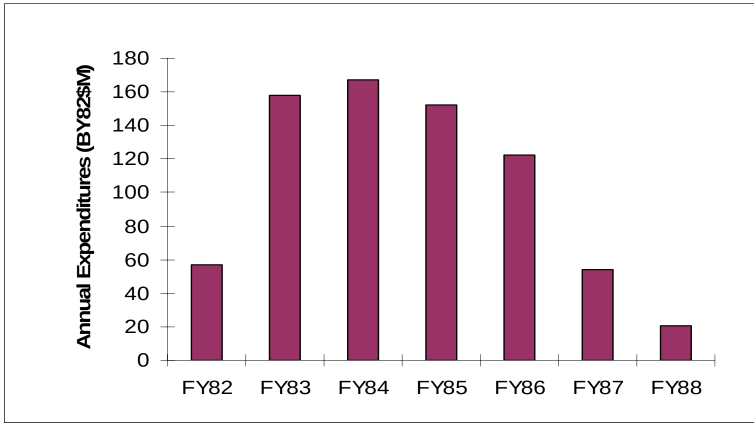
WARNING: Do not use cost profiles for budgeting

- Required Budget Authority exceeds expected costs incurred in early program years
  - Even if all budget is obligated each year
  - Difference published by DoD (outlay rates)

- Two analytical procedures for converting cost to budget proposed by Lee et al. (1997)
  1. Constrained nonlinear estimation
  2. Linear system with truncation
     - Easy to implement, distribute as spreadsheet tool
     - No iteration required

Cost-to-Budget Mechanics

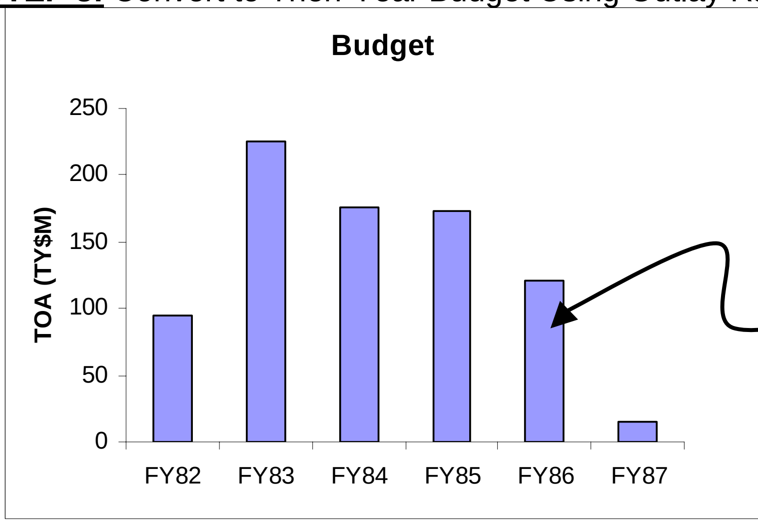
STEP 1: Estimate Time-Phased Expenditures in BY$



STEP 2: Convert to Real Dollars using raw indices

Fiscal Year	Raw Inflation Index	Expenditure Rate BY82$K	Expenditure Rate $K (Real $)
FY82	1.000	56653	56653
FY83	1.049	157796	165528
FY84	1.089	166918	181774
FY85	1.126	152075	171236
FY86	1.157	122438	141661
FY87	1.189	54209	64454
FY88	1.224	20297	24844
TOTAL		730387	806150

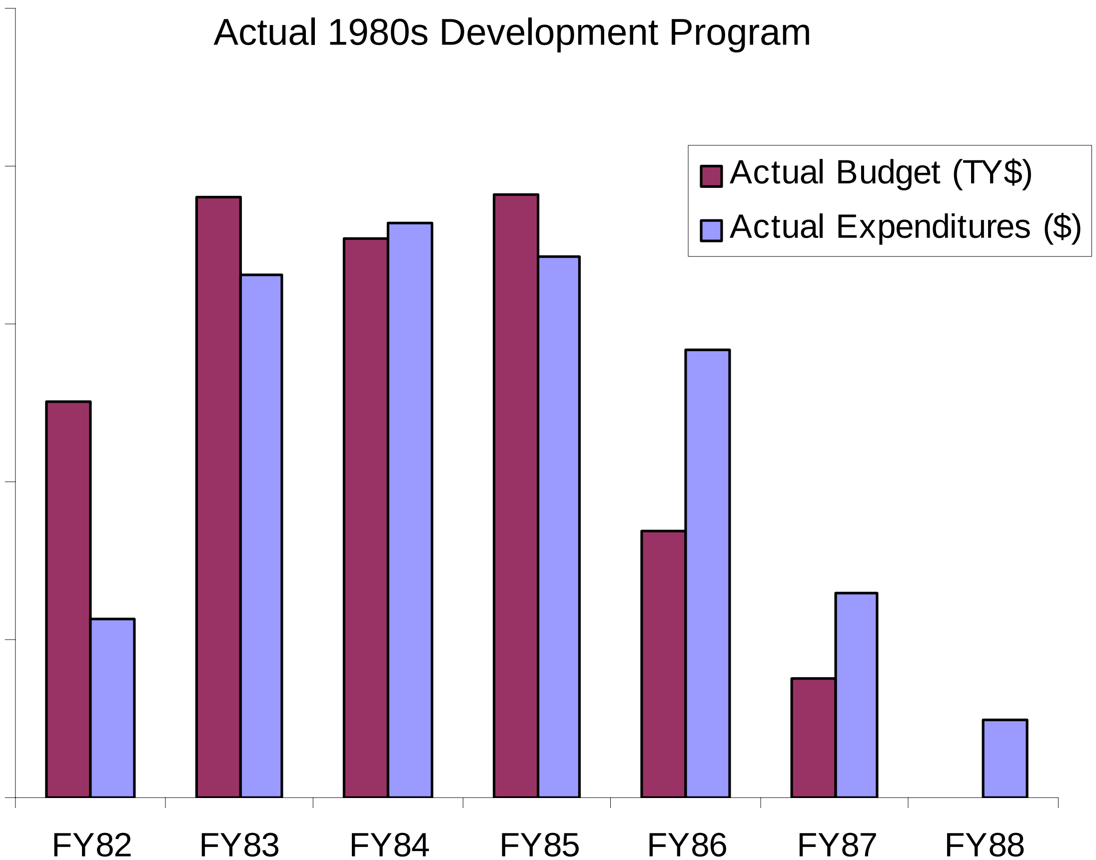
STEP 3: Convert to Then-Year Budget Using Outlay Rates



Solve linear system:

$$TOA_k = (\varepsilon_k - s_2 TOA_{k-1} - s_3 TOA_{k-2} - \cdots - s_J TOA_{k-J+1})/s_1$$

Resulting Budget vs. Expenditure Profile



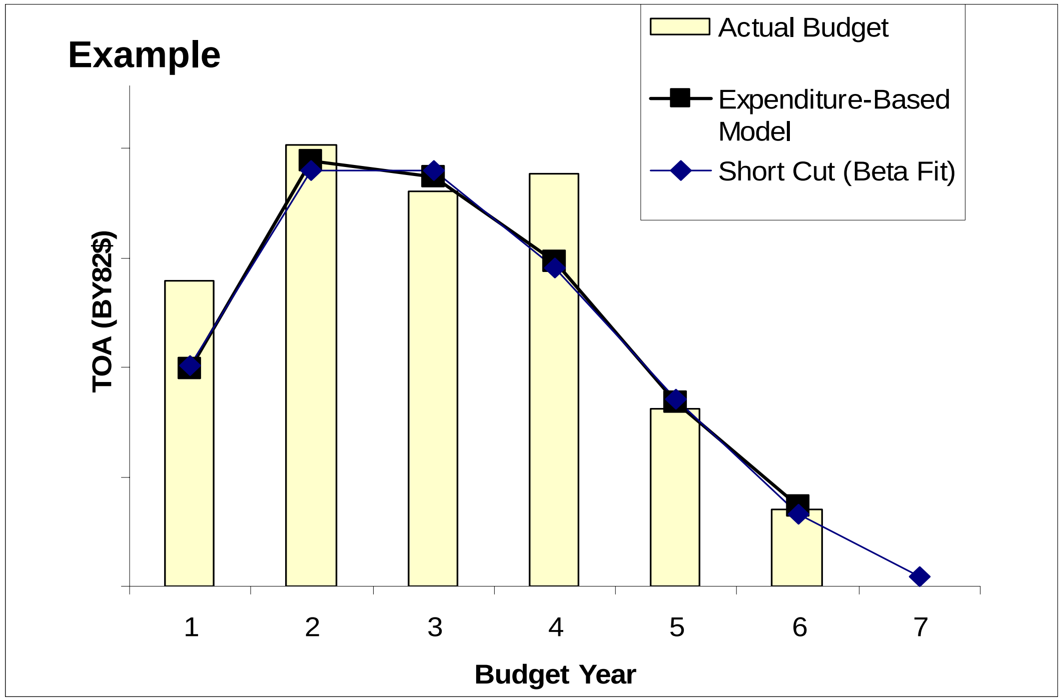
Often a big difference between cost and budget profiles

Short-Cut Approach

- Converts costs directly to budget profile
  - No other calculations involved
  - Based on same underlying 60/50 Rayleigh model (38% peak)
  - Assumes AF 3600 RDT&E outlay rates
- Uses Beta distribution

Number of Program Years	Alpha	Beta
3	2.65	5.69
4	2.47	4.95
5	2.11	3.87
6	1.97	3.38
7	1.90	3.10
8	1.88	3.00
9	1.86	2.88
10	1.84	2.80

Use MS-Excel "BETADIST" Function



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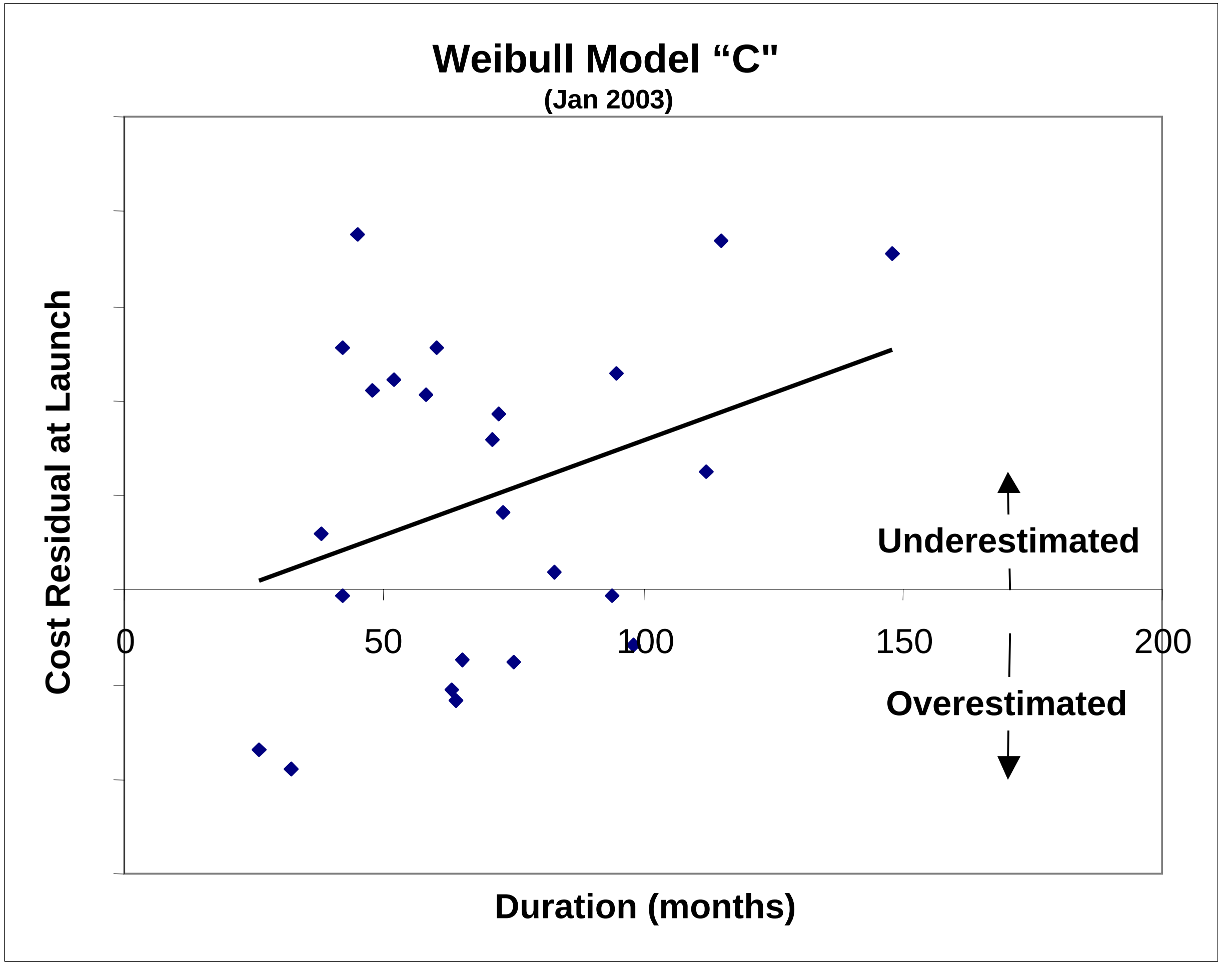
Space-System Phasing Model: Ground Rules

- Space-segment costs
  - Generally includes space SEIT/PM
  - Does not include Systems Integrator, CAAS/SETA, etc.
- Expenditures, not budgets
- Based on actual costs and schedules of completed contracts (26 NRO and Air Force)

Weibull-Based Model Underestimates Launch-Year Costs



…especially for long, multi-unit programs

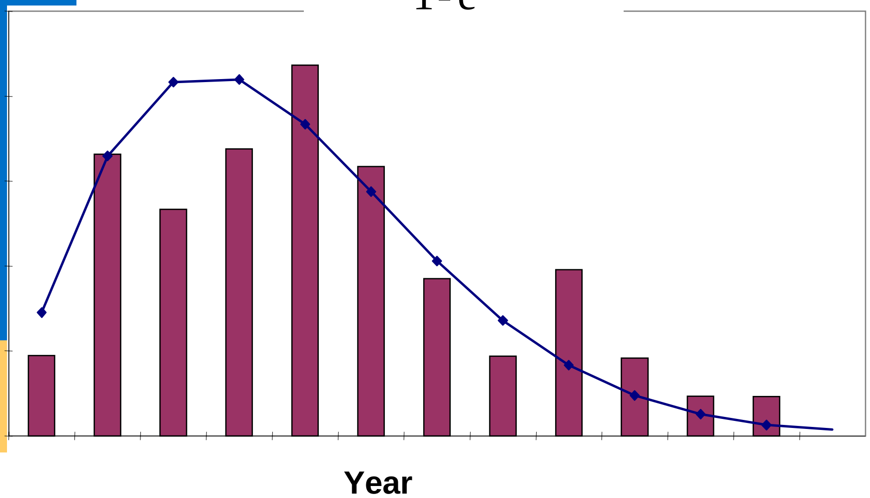
Solution: Modify Weibull Curve Form

- Add term that represents a constant expenditure rate (*R*):

Weibull Function

$$E(t) = d\left[1 - e^{-\alpha t^{\beta}}\right]$$

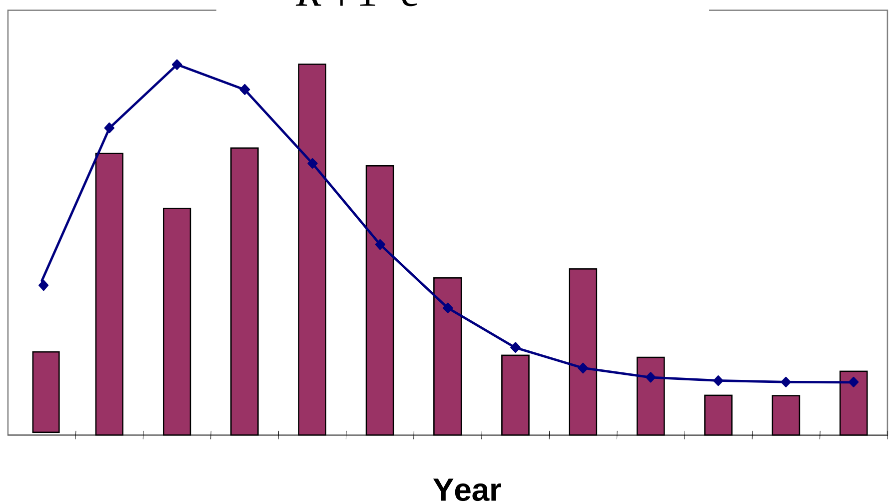
$$d = \frac{\text{total cost}}{1 - e^{-\alpha}}$$



Weibull + Constant Rate (R)

$$E(t) = d\left[Rt + 1 - e^{-\alpha t^{\beta}}\right]$$

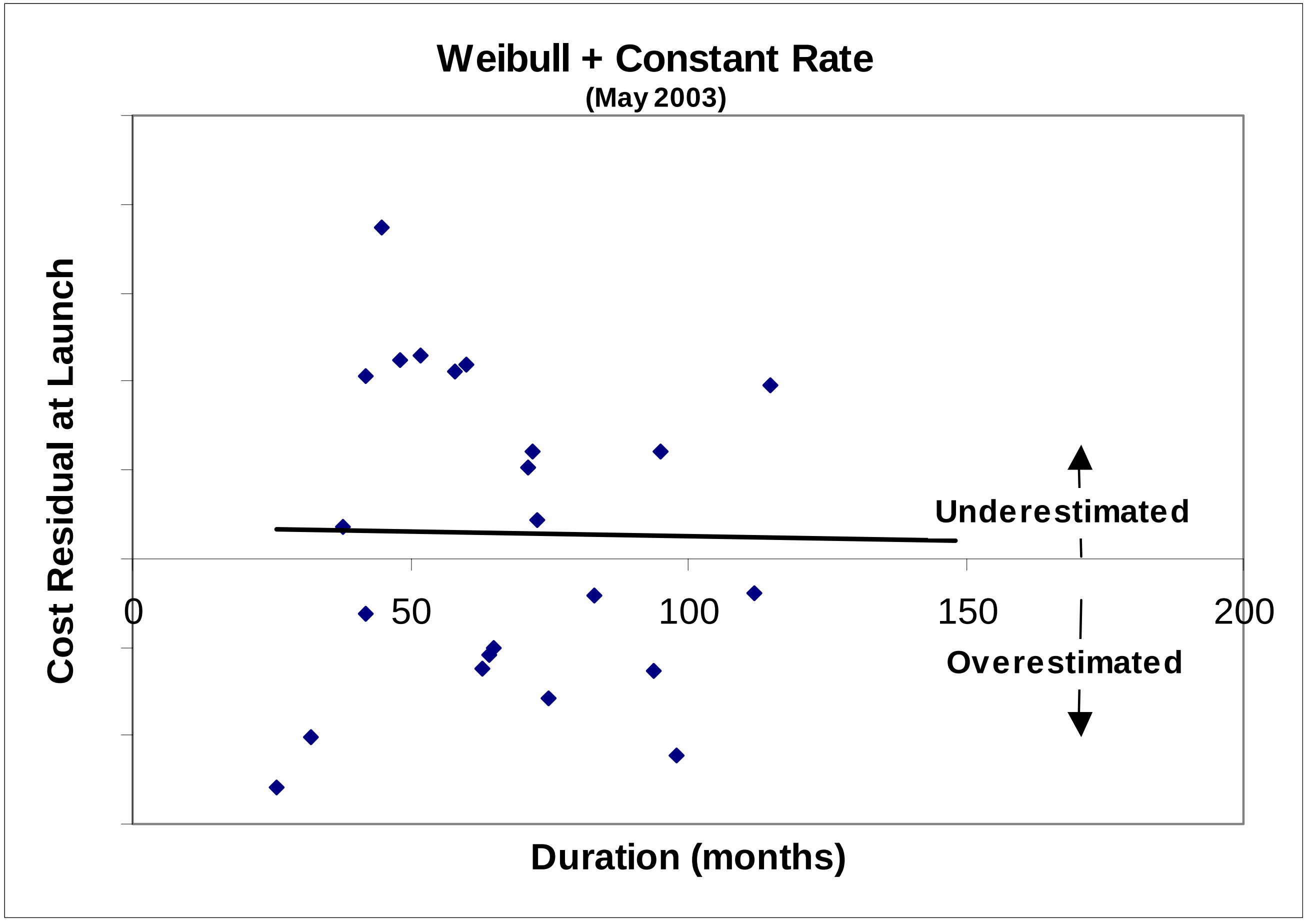
$$d = \frac{\text{total cost}}{R + 1 - e^{-\alpha}}$$



- Rate, *R*, is a function of duration
- Improves launch-tail and overall accuracy of phasing model

Launch-Year Expenditures: New Model

Near-zero bias for short and long programs



Result: Weibull + Constant-Rate Model

Method	Drivers	SD of Cum. Residuals	SD of Cum. at 40% complete	Pearsons R^2 of Exp. Rate	CV of Exp. Rate
Weibull Model C	α = f(units, duration, %NR) β = 1.71	6.3%	9.9%	0.72	33%
Weibull + Constant Rate	α = f(units, duration, %NR) β = 1.71 R = f(duration)	6.3%	9.8%	0.73	32%

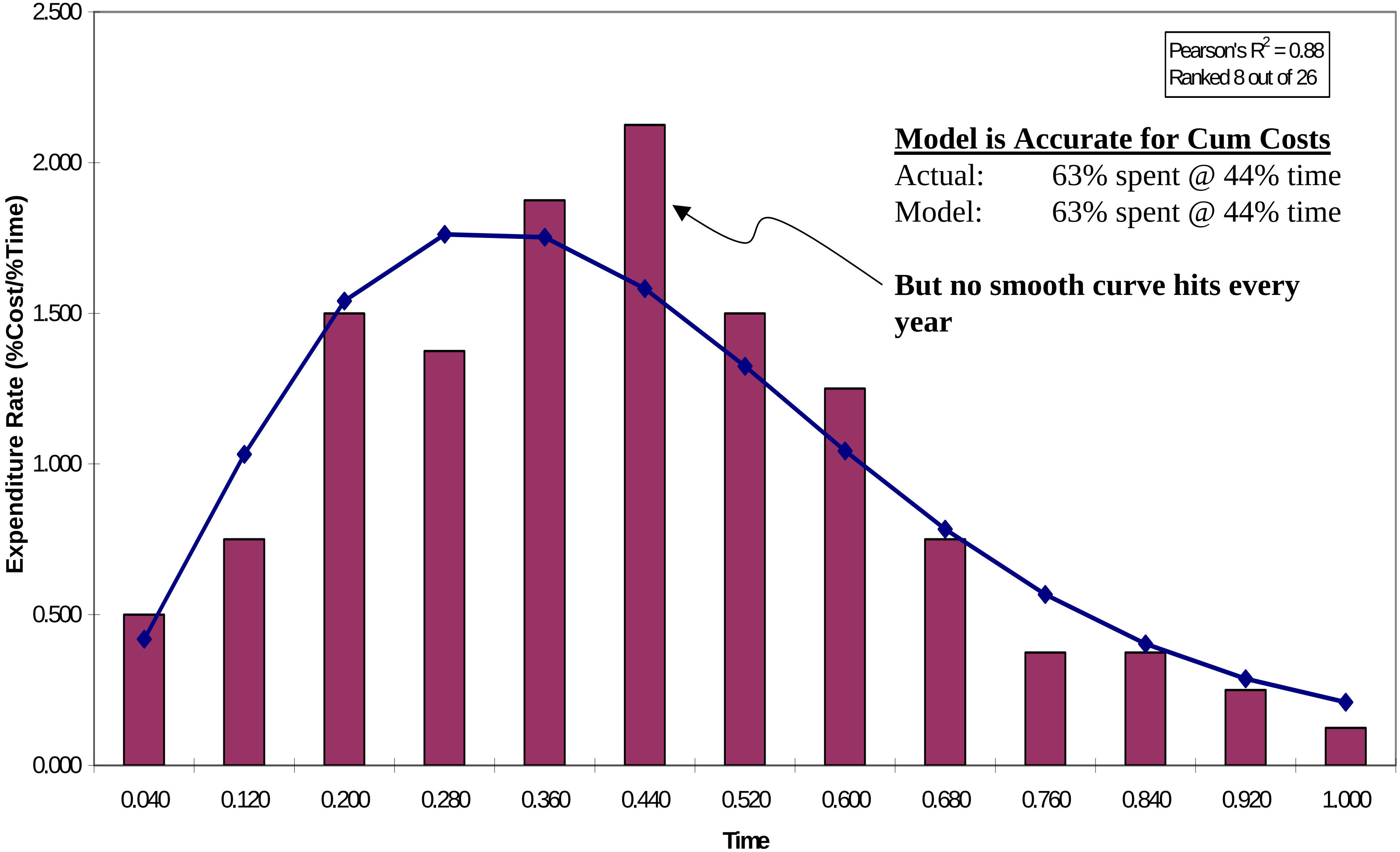
- **Weibull + Constant Rate** model is marginally better in 3 of 4 metrics, and solves launch-year issue
- Rate term is proportional to program duration

$$E(t) = d\left[Rt + 1 - e^{-\alpha t^{\beta}}\right]$$

$$d = \frac{\text{total cost}}{R + 1 - e^{-\alpha}}$$

t = cumulative time/total time
α = -.414 + .0729*(units) + .0488*(months duration) + .0145*(percent nonrecurring)
β = 1.71
R = .00148*(months duration)

Typical Profile: Good or Bad Fit?



Satellite Schedule Model: Ground Rules

- Schedule duration is from contract award to first-launch availability
  - Launch availability for first satellite in series
  - If not stored, then launch availability date = launch date
  - If stored, then launch availability = launch date minus factory storage time
  - Consistent with time-phasing model

- Multiple independent variables investigated
  - Dry weight
  - Power
  - Design Life
  - Orbital regime
  - Year of Award
  - NR/AUC Ratio
  - New vs. Replacement Capability
  - Qual/protoflight approach
  - Execution rate compared to phasing model
  - Number of distinct payloads
  - Time from award to Preliminary Design Review (PDR)

Satellite Schedule Model: Development Process

- Multiple databases assembled, investigated
  - All data
  - Govt only
  - Gov't only, no Class C/D (experimental smallsats)
  - Gov't only, new
  - Military only (NRO, AF, Navy)
  - NRO only
- Several stratification variables assessed
  - IMINT/Remote Sensor
  - SIGINT
  - Class C/D (experimental smallsats)
  - LEO Orbit
  - Commercial
  - NRO vs. AF/Navy
  - MIL vs. NASA

Programs in Database

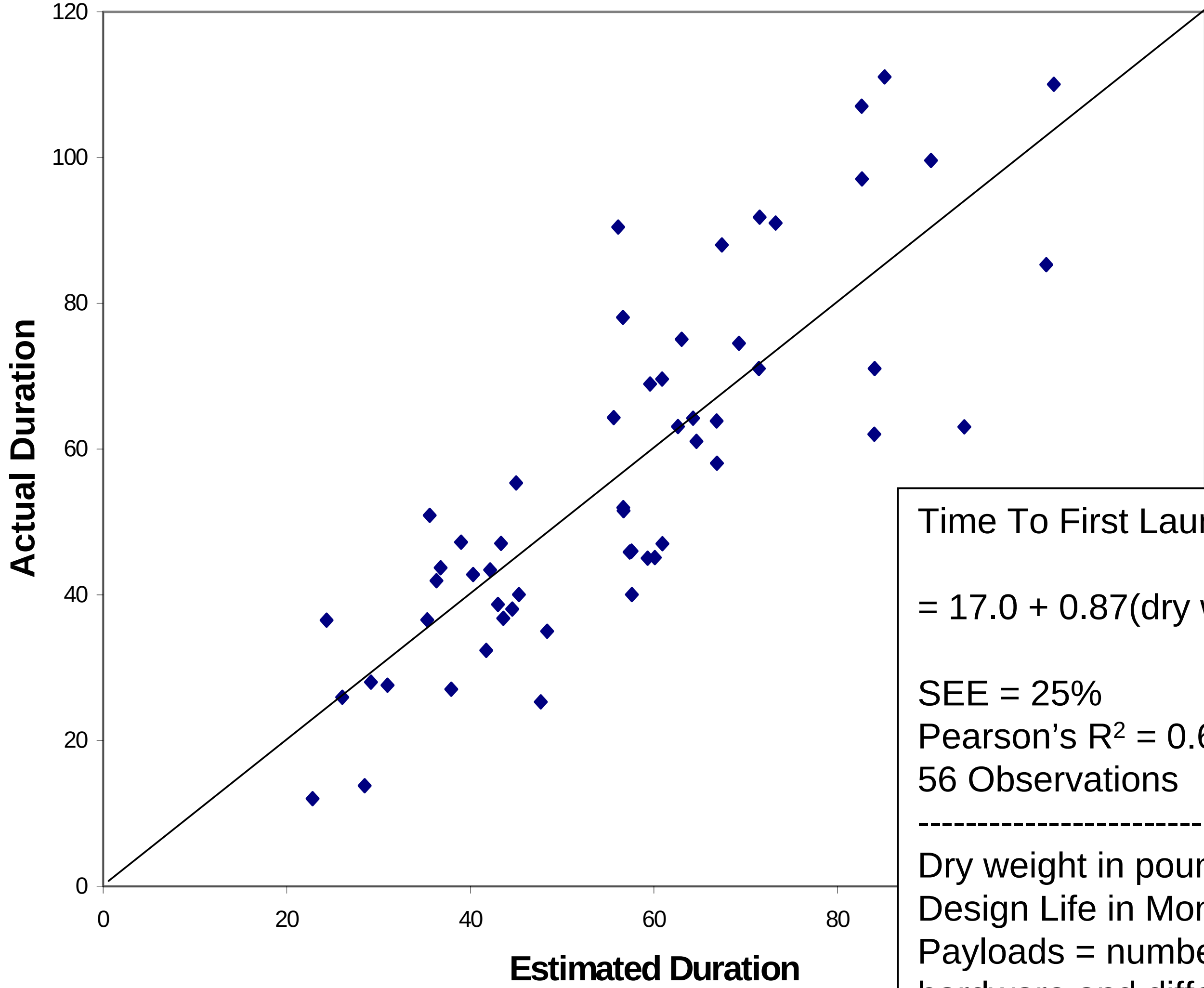
33 NASA
34 NRO
22 Military
22 Commercial

Over 150 Models developed and compared

Satellite Schedule Model: Findings

- Must segregate NASA, Commercial programs
  - Different drivers
  - Different durations for same drivers
- Class C/D (a.k.a. experimental) not a driver
  - Technical aspects of program are sufficient (short design life and low weight)
- NR/AUC ratio not a driver in any data subset
- NR+T1 cost is a poor predictor
- BOL power is a poor performer compared to weight
  - In all data subsets
  - In combination with all other variables investigated

Schedule Model: NRO+AF Dataset



Time To First Launch Availability (TT1L)

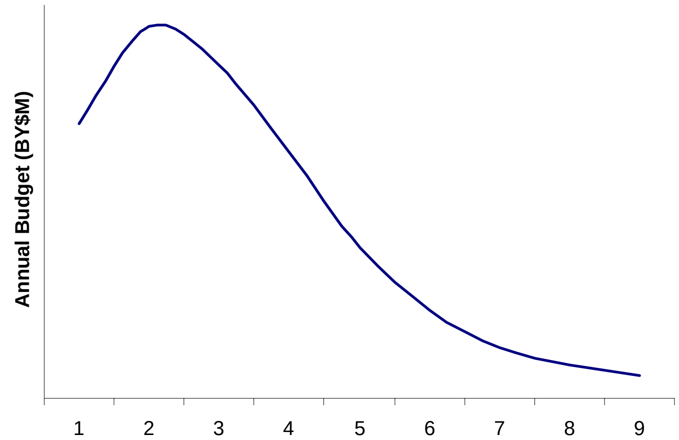
$= 17.0 + 0.87(\text{dry wt})^{.406} (\text{DesLife*Payloads})^{.136}$

SEE = 25%
Pearson's $R^2 = 0.69$
56 Observations

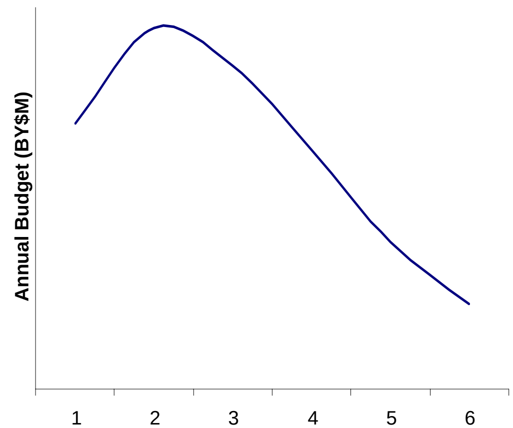
Dry weight in pounds
Design Life in Months
Payloads = number with physically distinct hardware and different users

Schedule-Phasing Interaction

- If Schedule Model Estimates Long Duration (~90+ months)
  - Phasing model is front loaded
  - Typical 80/50



- If Schedule Model Estimates Average Duration (~65 months)
  - Phasing model more "even"
  - Typical 60/50



Summary

- Predictive accuracy can be measured several ways
- Use of independent variables to drive profile shape improves accuracy
  - Single-stage regression gives better results than traditional multi-stage approach
  - Choice of functional form (e.g., Beta/Rayleigh/Weibull) has little effect on accuracy of final model
  - 60/50 Rayleigh is good choice for most development programs
- Start and end-dates must be well defined
  - Don’t phase to PM’s aggressive schedule
  - Use independent schedule estimate
- Cost profiles are not budget profiles

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