Determining Cost Estimating Relationships for Nine FAA Solution Development Elements

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Abstract

The Federal Aviation Administration is responsible for management of our National Airspace System, which requires massive amounts of software development and maintenance. The writing and testing of large-scale software is expensive and involves many substantial costs in addition to the development of the basic software itself.

In an effort to improve financial management practices within the FAA, new Cost Estimating Relationships (CERs) were determined for nine FAA Work Breakdown Structure elements pertaining to software development and delivery life cycles activities.

CERs are regression equations typically based on normalized actual costs of prior analogous software development. However, these new CERs are based on budget Resource Planning Documents (RPD) data instead of actual costs because the RPDs are the largest set of well-maintained cost data available within the FAA. Depending on CER hypothesis, the source data is derived from 52 to 83 FAA program RPDs of small (<$1M) to large (>$500M) life cycle value.

We show the methodology, regression results and statistical accuracy of new CERs available for the FAA to use in estimating costs for nine WBS elements of software development.

The determination of these CERs from using deductions about the data variables may be considered, from a purely mathematics perspective, as a regularized ill-posed and ill-conditioned inverse modeling problem in calculating the values of the CER parameters obtained from the planned budget (not actuals) data.

Determining Cost Estimating Relationships for Nine FAA Solution Development Elements

- Background
- The Problem
- The Method
- The Results
- Questions, Comments

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Background

- **The FAA mission:**
  - Provide the safest, most efficient aerospace system in the world
- **Major FAA roles:**
  - Develop and operate a system of air traffic control and navigation for both civil and military aircraft
  - Regulate civil aviation to promote safety
  - Research and develop the Next Generation Air Traffic Control System for the National Airspace System and for civil aeronautics
  - Ensure new, proposed, and existing NAS *investments* meet established business case and economic criteria
  - **See also** ***http://www.faa.gov/about/mission***

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Background

Two typical methodologies used to estimate investment costs for development, implementation, and maintenance of software:

- ***Cost Factors*** provide percentage multipliers against the historical cost of Development hardware (H/W) & S/W or Production H/W.
  - FAA factors were developed in 2002 from a survey of Department of Defense, Industry, and FAA sources
  - A problem with factors is they require a good understanding of the software and its environment to determine which factor to apply
- ***Cost Estimating Relationships (CERs)*** are equations derived by regression of normalized actual costs of prior analogous development, implementation, and maintenance
  - CERs may be confidently used and do not typically require detailed specifications or technical understanding

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The Problem - Existing FAA Cost Factors

FAA ASD-410 Pocket Estimating Guide		*** Coordinate with ASD-410 before use ***				12 Dec 01 Ver 0.33
WBS	***DEVELOPMENT***	**Low Tendency**	**Low**	**ML**	**High**	**High Tendency**
3.2	System Engineering	Hardware Intensive	31%	**60%**	86%	Software Intensive
3.3.1.2	*Hardware less NRE, AUC	All COTS	100%	**150%**	200%	New Development
3.3.3	HW/SW Integ., Ass'y, Test & Chkout	Hardware Intensive	10%	**16%**	24%	Software Intensive
3.4.1	Facility Planning & Design	Software Intensive	2%	**24%**	47%	Hardware Intensive
3.5.1	System Dvlpmt. Test & Eval.	Minor Modification	5%	**15%**	27%	New Capability
3.6	Documentation	Minor Modification	1%	**21%**	27%	New Capability
3.7.3	Support & Hdlg Equip. Acq. (CSE)	Minor Modification	2%	**8%**	11%	New Capability
3.7.4	Support Fac. Const. / Conv. / Exp.	Software Intensive	10%	**14%**	20%	Hardware Intensive
3.7.5	Support Equip. Acq. / Mod. (PSE)	Minor Modification	1%	**10%**	34%	New Capability
3.7.7	Initial Spares & Repair Parts Acq.	Software Intensive	1%	**19%**	39%	Hardware Intensive
3.7.8	Initial Training	Minor Modification	1%	**10%**	17%	New Capability
Factors applied to sum of (WBS 3.3.1 Hdw + WBS 3.3.2 SW) with exception of WBS 3.3.1.2						
*Factor applied to WBS 3.3.5, Production, Average Unit Cost (AUC)						

What is the **FAA** WBS?

Work breakdown structure. A hierarchical decomposition of the work to be performed to accomplish an approved agency objective. It includes both internal and external work activities and each descending level represents an increasing definition of the work to be performed.

FAA Acquisition Management System, Appendix C.

FAA ASD-410 Pocket Estimating Guide		*** Coordinate with ASD-410 before use ***				12 Dec 01 Ver 0.33
WBS	***PRODUCTION***	**Low Tendency**	**Low**	**ML**	**High**	**High Tendency**
3.3.4	Prod. Engineering (Prod. SE/PM)	Hardware Intensive	12%	**27%**	40%	Software Intensive
3.4.3	Physical Infrastructure	Software Intensive	7%	**13%**	21%	Hardware Intensive
3.5.4	Site Acceptance Testing (Prod. ST&E)	Minor Modification	5%	**7%**	10%	New Capability
3.6	Documentation	Minor Modification	4%	**6%**	10%	New Capability
3.7.3	Support & Handling Equip. Acq. (CSE)	Minor Modification	1%	**2%**	3%	New Capability
3.7.5	Support Equipment Acq. / Mod. (PSE)	Minor Modification	2%	**10%**	23%	New Capability
3.7.6	Support Facilities & Equip. Maint.	Software Intensive	1%	**2%**	3%	Hardware Intensive
3.7.7	Initial Spares & Repair Parts Acq.	Software Intensive	7%	**15%**	37%	Hardware Intensive
3.7.8	Initial Training	Minor Modification	1%	**2%**	3%	New Capability
4.6	Installation & Checkout	Software Intensive	18%	**20%**	34%	Hardware Intensive
5.3	Modifications	Software Intensive	20%	**30%**	40%	Hardware Intensive
5.8.1	Supply Support	Software Intensive	5%	**7%**	10%	Hardware Intensive
5.8.2	Repair	Software Intensive	7%	**10%**	24%	Hardware Intensive
Factors applied to WBS 3.3.5, Production Hardware						

The Problem – Buying a Lot of FAA Software

- The FAA is improving *Life Cycle Cost Estimates* in order to make informed investment decisions on the acquisition of NAS components

- Cost, the basis of an investment decision, is *difficult to estimate for software* because of the many elements, parameters and methodologies involved

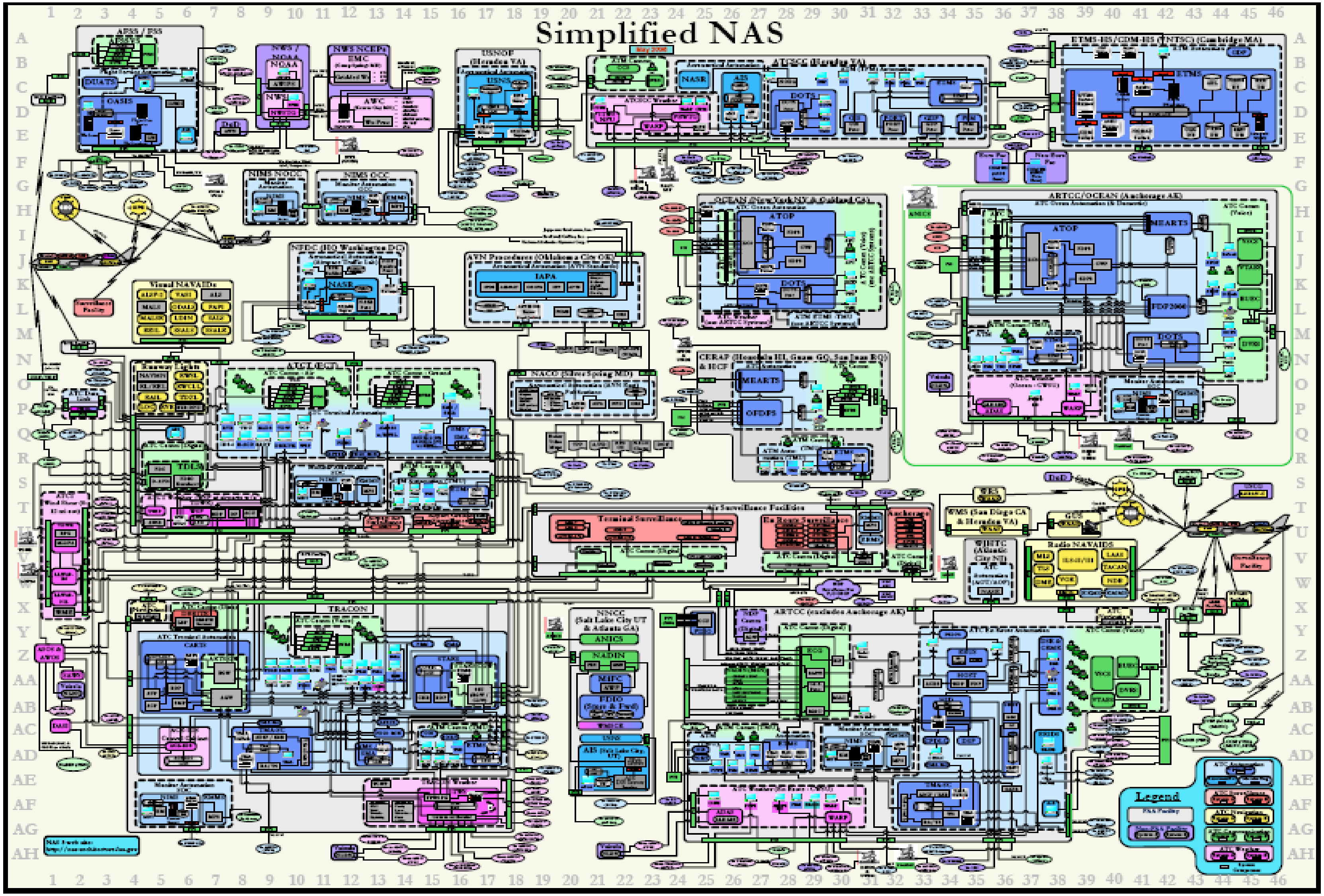
- The FAA needed a better method to estimate life cycle costs for WBS elements that are *significant cost drivers* of NAS software

– and there is a lot of FAA software!!!

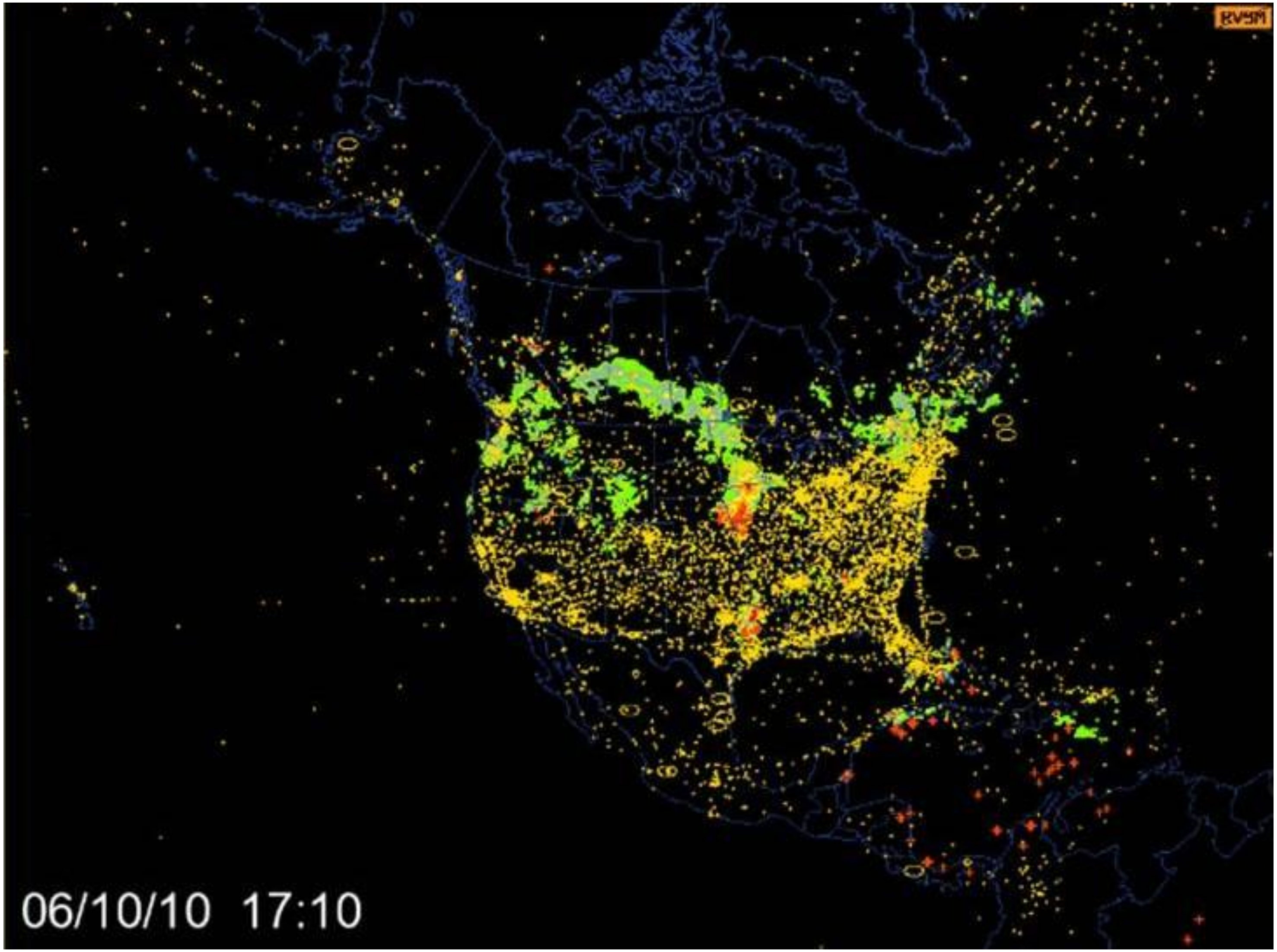
Just how much NAS software is there . . .

. . . a massive amount of software . . . . which controls . . .

(of course you really can't read this!)



. . . a lot of North American airspace.



Snapshot of typical North American airspace at noon EST (5:10 PM Zulu) on June 10th.

Legend:

Yellow – each dot is an aircraft above 1000 ft.
Green – Convective weather
Red – Lightning strikes
Ovals – A/C in holding pattern

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Overview of the CER Development Process

- Surveyed FAA systems for program-specific cost data – every FAA program has a Resource Planning Document (RPD) with
  - Program *baseline costs,*
  - Which are *time phased*, and
  - Are in accordance with the *FAA WBS*
- Selected those RPDs having (see Characterization of RPDs for details)
  - Achieved at least 70% of their life cycle (range from 3 to 15 years)
  - Non-zero Hardware and/or Software costs, and
  - Non-zero dependent variable costs (e.g. Program Management, System Engineering, etc.)
- Normalized the data to $BY09
- Developed CERs using regression analysis and statistical tests
- Validated each CER by comparing to the old FAA Factors
- Present results to FAA

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The Usable RPD Data Sets

Potential RPD Data Points for CER Development		Non-Zero Value	And Non-Zero SW or HW	And Non-Zero SW and HW	Maximum Data Pts.	Minimum Data Pts.
3.1	Program Management	116	76	42	76	42
3.2	System Engineering	126	61	47	61	47
3.3.1	Hardware Design and Dev	65	33	36	36	33
3.3.3	HW/SW Integration, Assembly, Test and Che	61	83	37	61	37
3.3.4	Production Engineering	33	37	18	33	18
3.4	Phys / Airspace Infrastructure Dsn / Dev	37	29	17	29	17
3.5	Test and Evaluation	58	8	44	44	8
3.6	Data and Documentation	86	16	34	34	16

FAA WBS

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Reminder – OLS Regression

- Ordinary Least Squares Regression - a statistical technique used to predict the behavior of a dependent variable
- A *linear regression equation* takes the form of **Y=a+bx+c**
  - **Y** is the dependent variable being predicted
  - **x** is the independent variable used to predict **Y**
  - **a** is the **Y**-intercept of the line
  - **c** is the regression residual
- "Best" fit is achieved when
  - the values of **a** and **b** are selected so that the square of the regression residuals is minimized,
  - a correlation coefficient is maximized, and
  - the sample t-test supports the null hypothesis that the IV is related to the DVs by at least x% correlation
- Assume the residuals are independent and identically normally distributed
- Caution - correlation does not prove causation!

Stat 101

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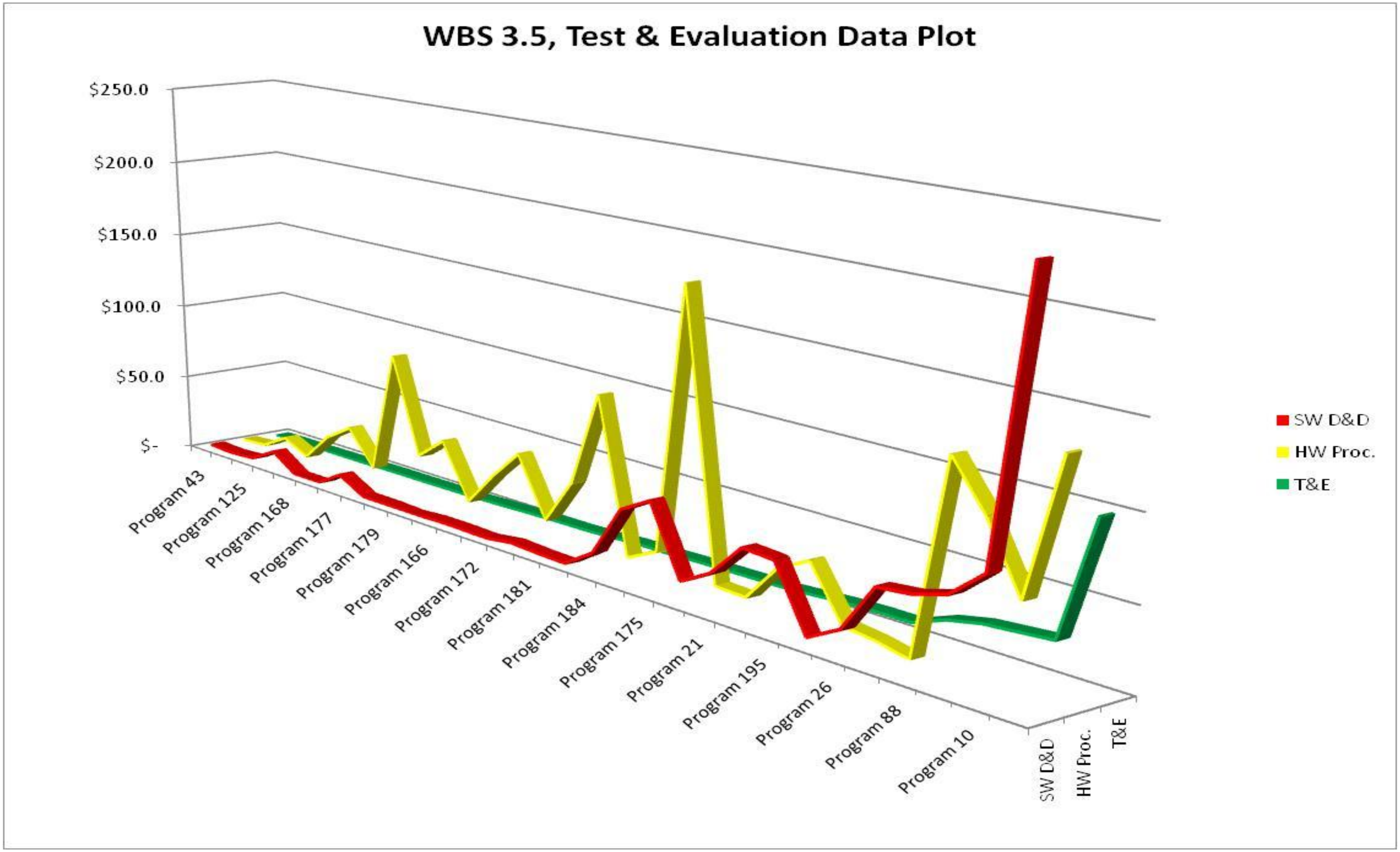
Steps for Developing Each CER

1. Identify & Visualize the normalized Data Set
   - Identify independent and dependent variables
   - Graph relationship between dependent variable costs in increasing rank and the independent variables of Hardware and Software

2. Conduct statistical analysis and test linear and non-linear regressions to select a Best CER based on:
   - Sign of the Coefficients –negative and/or zero values not preferred
   - Fit statistics – significance of t-test, R^2, SE

3. Graphically compare Actual vs. Predicted cost

Step 1: Visualize the Data (Example for WBS 3.5, T&E)



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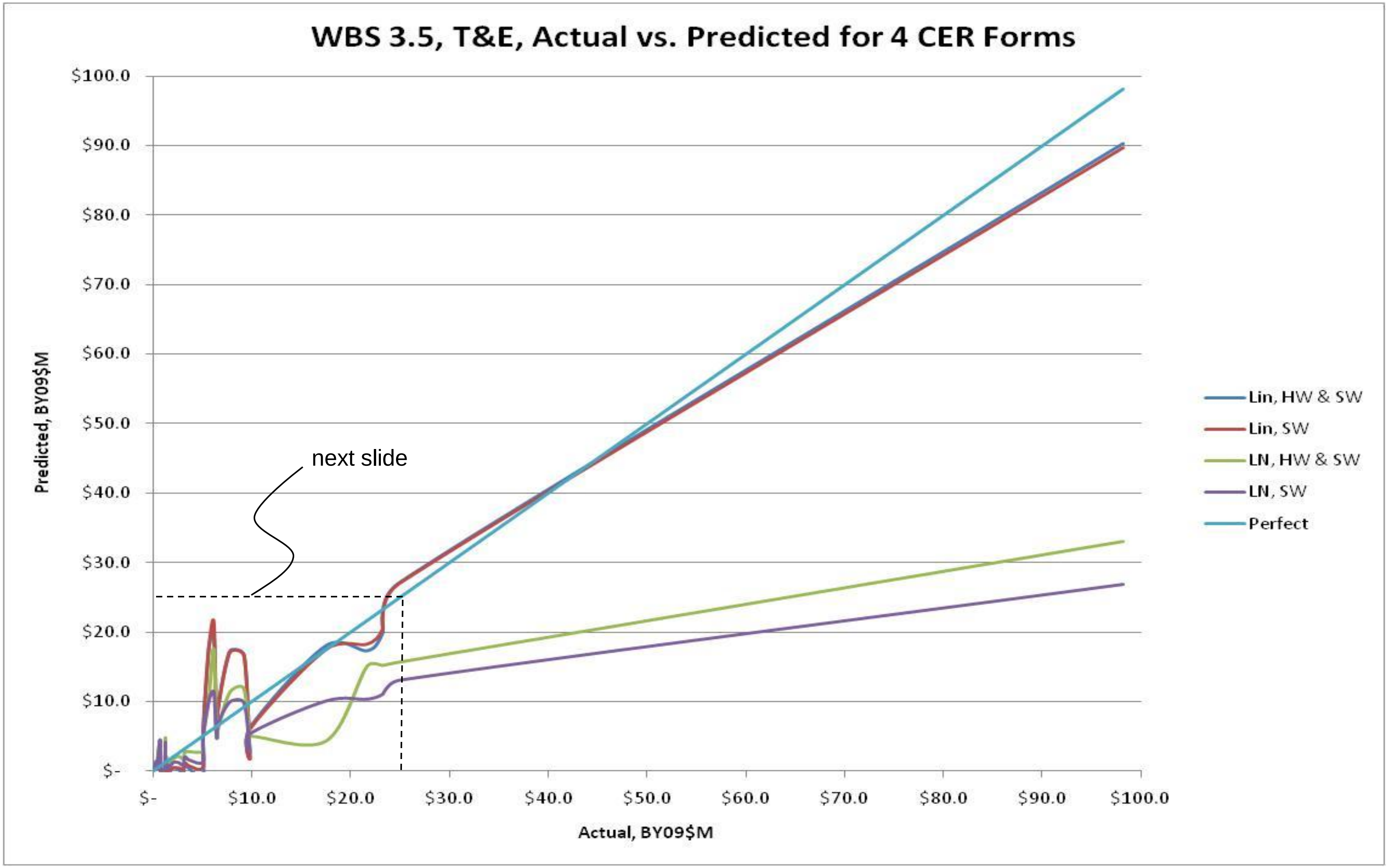
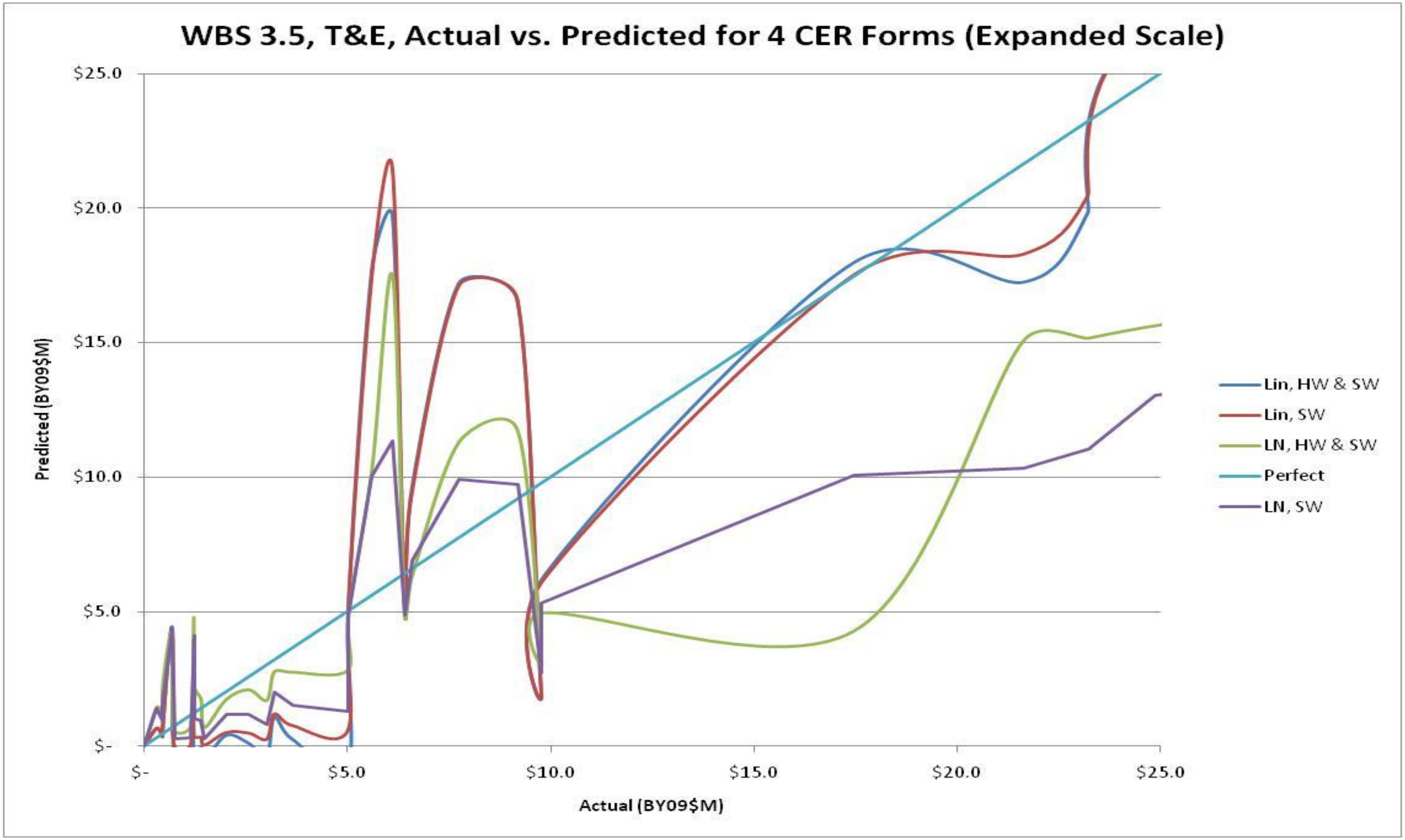
Step 2: Regression Results (Example for WBS 3.5, T&E)

- Linear, using both hardware and software as independent variables:
  - T&E = -0.01 * SW + 0.39 * HW, R^2 = 94%, t_{SW} = -0.6, t_{HW} = 15.7, SE = 5.2
  - Note negative SW coefficient, proximity of SW coefficient to zero, low t-statistic for SW
- Logarithmic, using both hardware and software as independent variables:
  - T&E = SW ^ 0.18 * HW ^ 0.48, R^2 = 81%, t_{SW} = 3.1, t_{HW} = 6.9, SE = 0.85
  - Note that R^2 is lower than with Linear form, should be higher due to transformation reducing overall variability
  - Note that HW coefficient more powerful than SW coefficient, but data plot does not support this result
- **Linear, using software as independent variable:**
  - **T&E = 0.38 * SW, R^2 = 94%, t_{SW} = 20.7, SE = 5.2**
  - **Note removing HW made major improvement to t-Statistic**
  - **This CER judged to be the "best" and was selected for WBS 3.5**
- Logarithmic, using software as independent variable:
  - T&E = SW ^ 0.60, R^2 = 74%, t_{SW} = 9.2, SE = 0.97
  - Note that R^2 is lower than with Linear form, should be higher due to transformation reducing overall variability
  - t_{SW} lower than with linear form

Step 3: Actual vs. Predicted Plot (Example for WBS 3.5 T&E)



Step 3: Actual vs. Predicted Plot, detail (Example of WBS 3.5 T&E)



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CER Development: Summary of Results
WBS 3 Solution Development

Cost Estimating Relationships derived for selected FAA WBS

Ref.	WBS		CER	R^2
1	3.1	Program Management	PM = 0.38 * SW + 0.21 * HW	92%
2	3.2	System Engineering	SE = 0.81 * SW + 0.06 * HW	94%
3	3.3.1	Hardware Design and Dev	HW Dsgn = SW ^ 0.29 * HW ^ 0.37	67%
4	3.3.3	HW/SW Integ., Ass'y, Test and Checkout	Integ = HW ^ 0.06 * SW ^ 0.44	74%
5	3.3.4	Production Engineering	Prod Eng = SW * .45 + HW * 0.01	78%
6	3.4	Phys / Airspace Infrastructure Dsn / Dev	PAIDD = 1.14 * SW	81%
7	3.5	Test and Evaluation	TE = 0.38 * SW	94%
8	3.6	Data and Documentation	Data = 0.01 * SW + 0.01 * HW	78%
9	3.7	Logistics Support	Log Spt = 0.07 * SW + 0.06 * HW	89%

Notes:

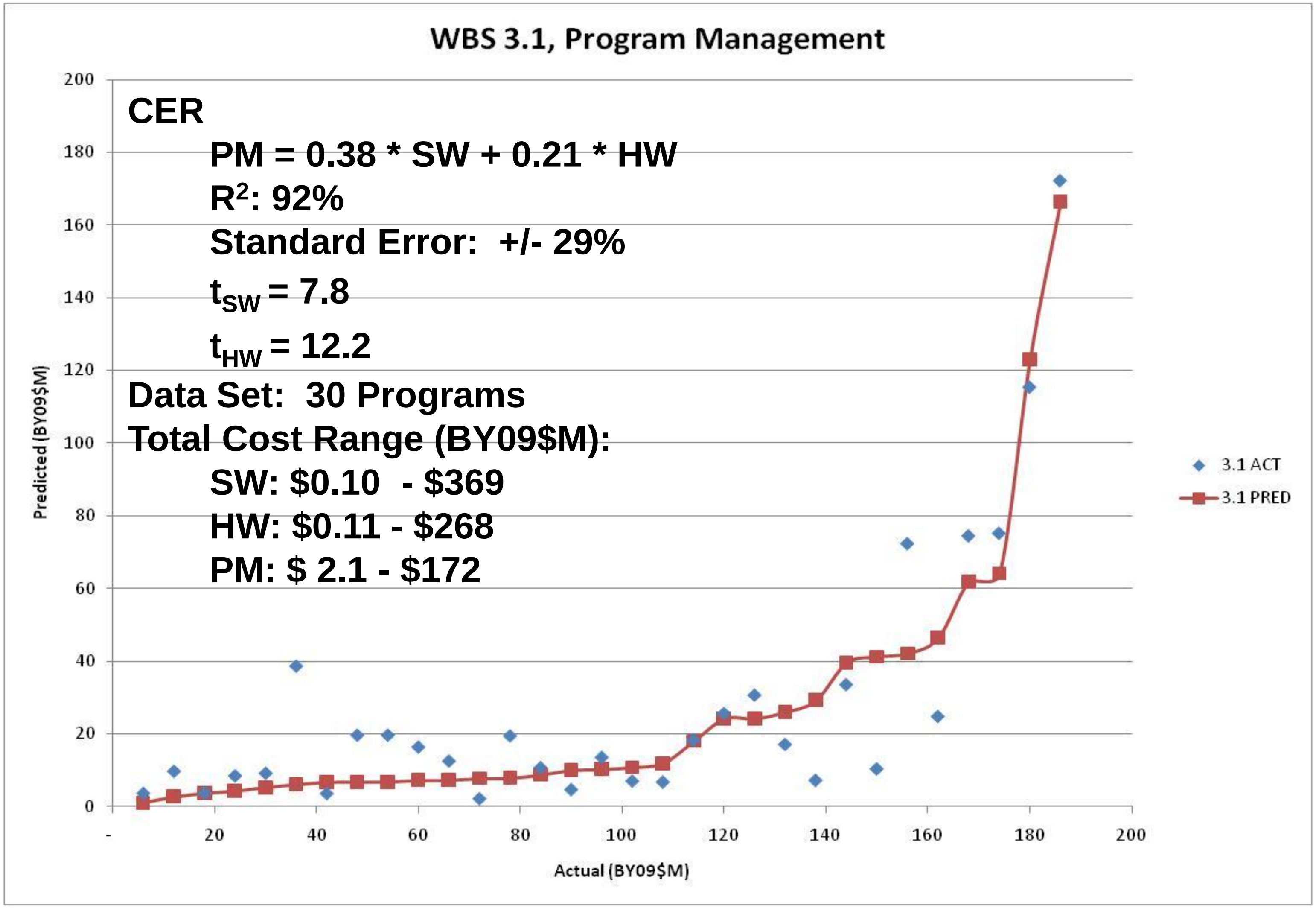
SW = Total cost from WBS 3.3.2, Software Design and Development

HW = Total cost from WBS 3.3.5, Hardware Procurement / Production

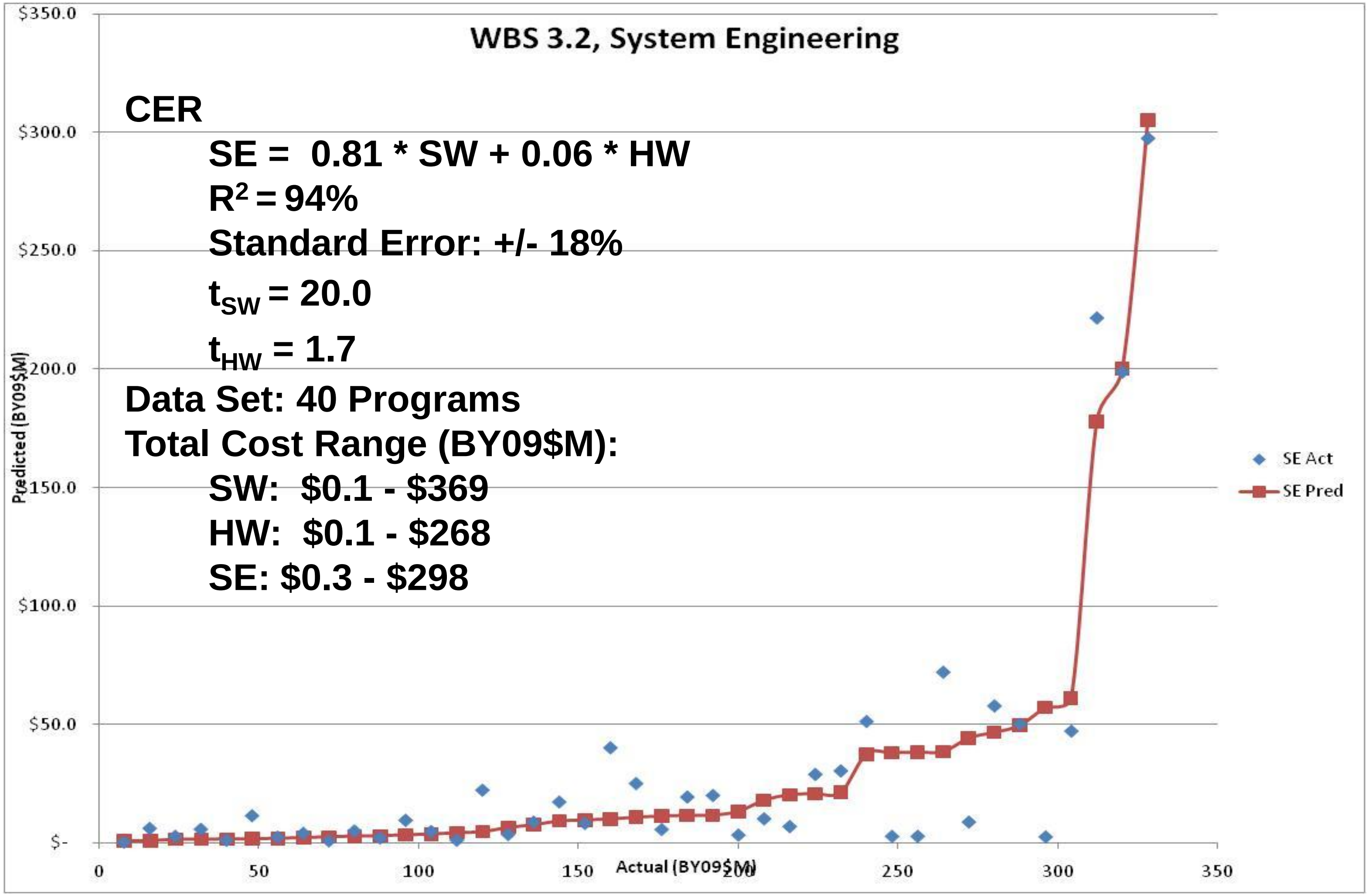
All CERs are based on baselined RPD costs, not on actual historical costs

Hi/Lo dollar range and descriptive statistics for each CER is in the following slides

Actual vs. Predicted Chart
WBS 3.1 Program Management



Actual vs. Predicted Chart
WBS 3.2 System Engineering



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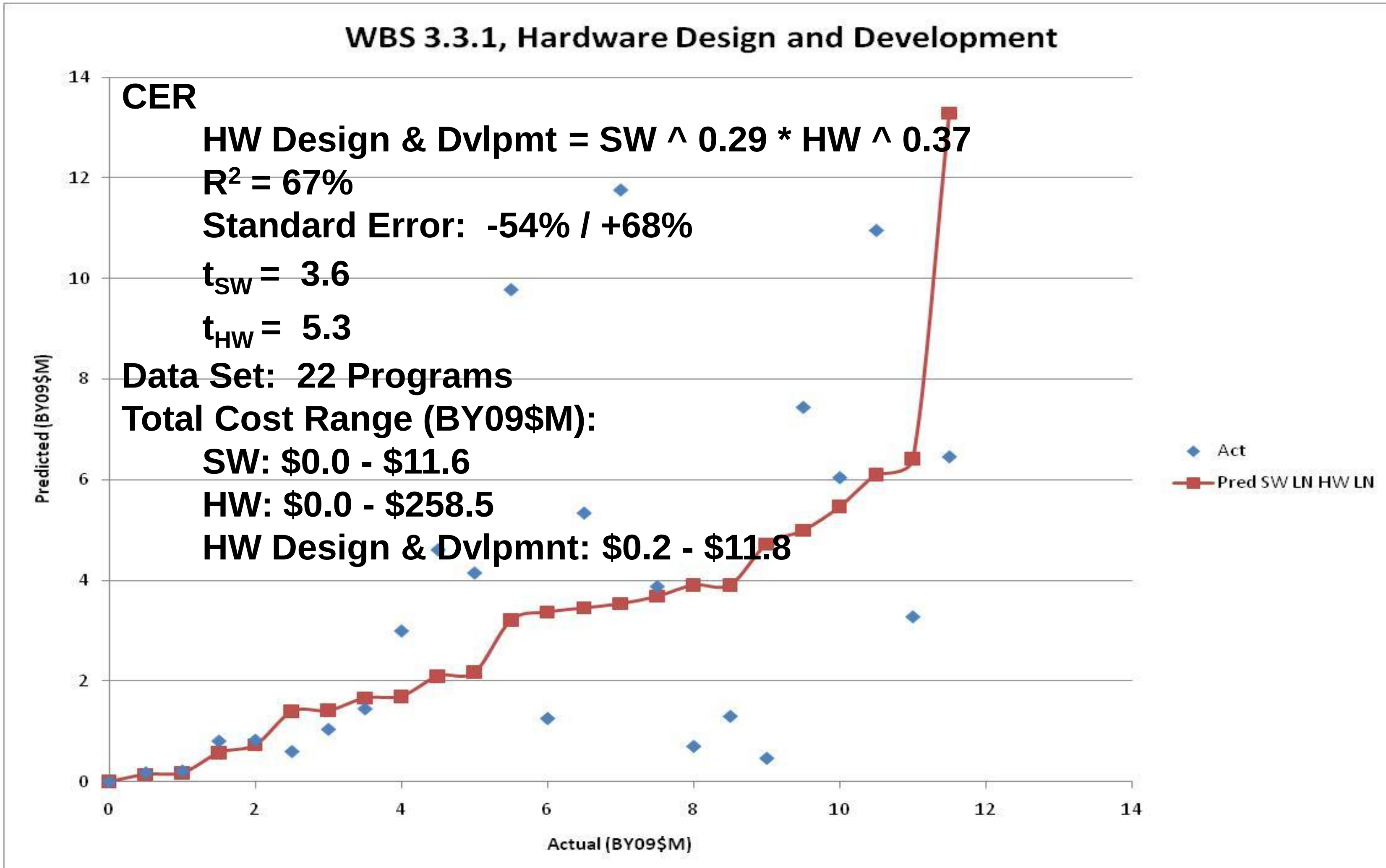
Actual vs. Predicted Chart
WBS 3.3.1 Hardware Design and Development



CER

- HW Design & Dvlpmt = SW ^ 0.29 * HW ^ 0.37
- R^2 = 67%
- Standard Error: -54% / +68%
- t_{SW} = 3.6
- t_{HW} = 5.3

Data Set: 22 Programs

Total Cost Range (BY09$M):

- SW: $0.0 - $11.6
- HW: $0.0 - $258.5
- HW Design & Dvlpmnt: $0.2 - $11.8

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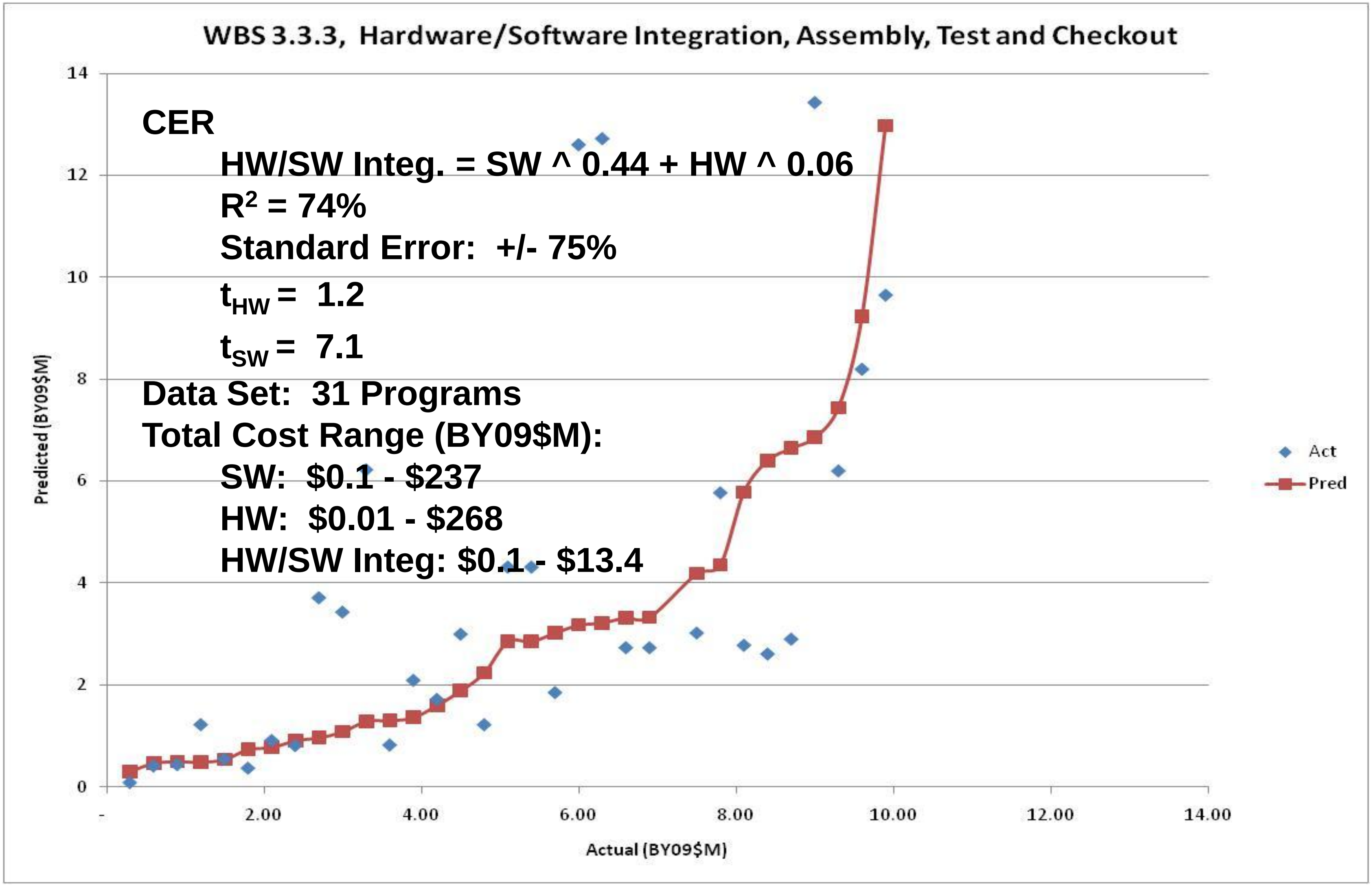
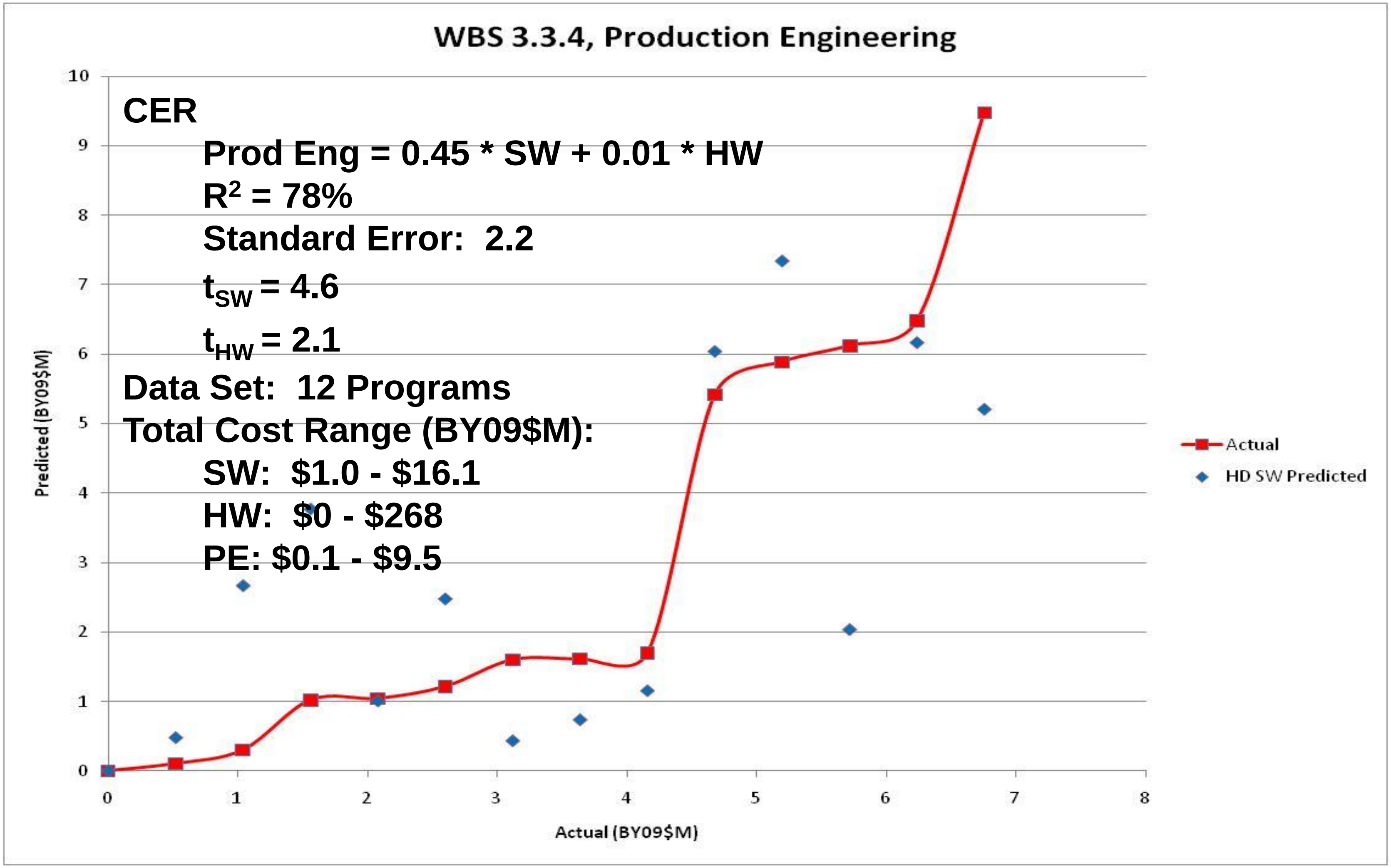
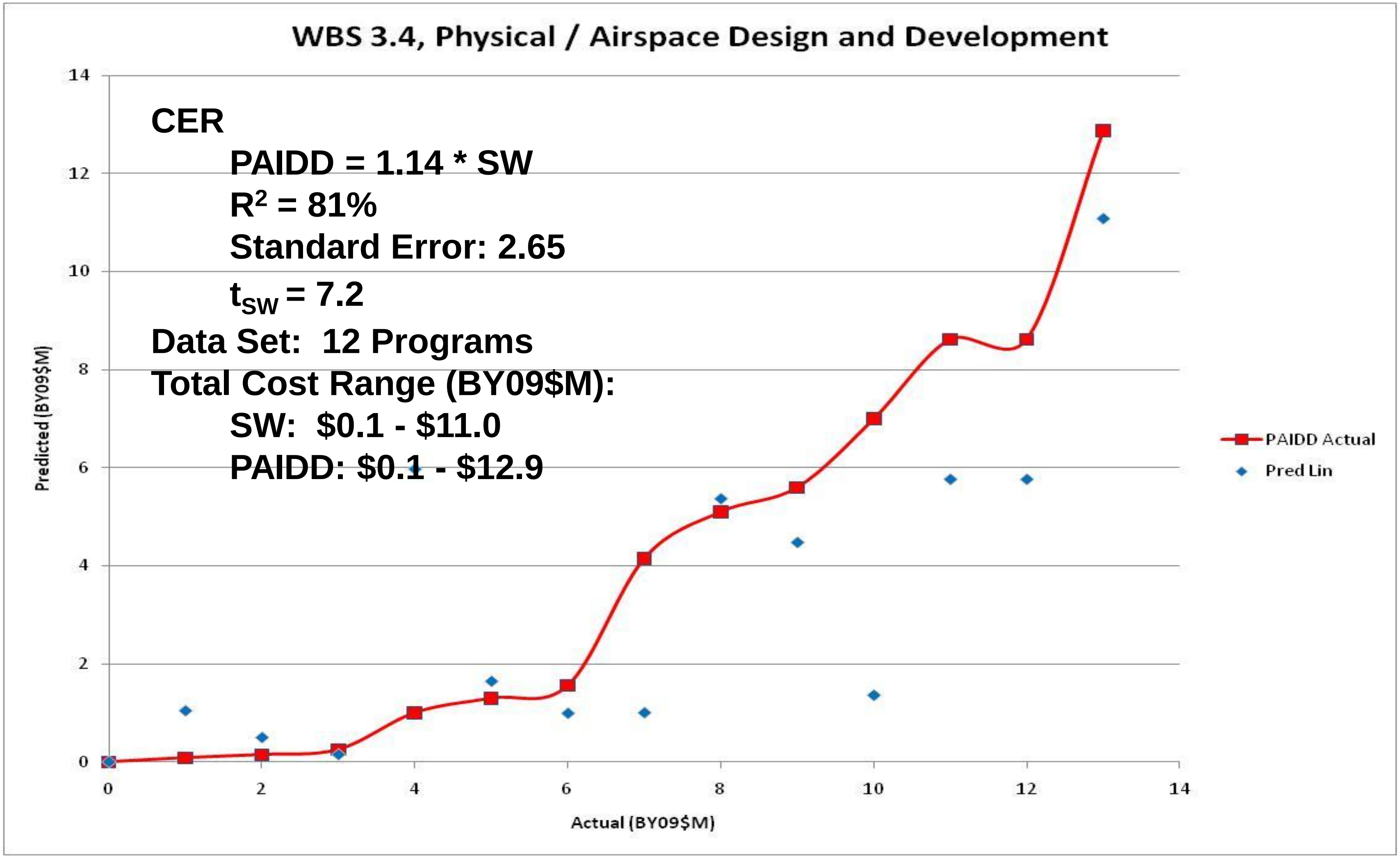
Actual vs. Predicted Chart
WBS 3.3.3 HW/SW Integration, Assembly, Test and Checkout



Actual vs. Predicted Chart
WBS 3.3.4 Production Engineering



Actual vs. Predicted Chart
WBS 3.4 Physical/Airspace Infrastructure Design & Development



CER

PAIDD = 1.14 * SW

R^2 = 81%

Standard Error: 2.65

t_{SW} = 7.2

Data Set: 12 Programs

Total Cost Range (BY09$M):

SW: $0.1 - $11.0

PAIDD: $0.1 - $12.9

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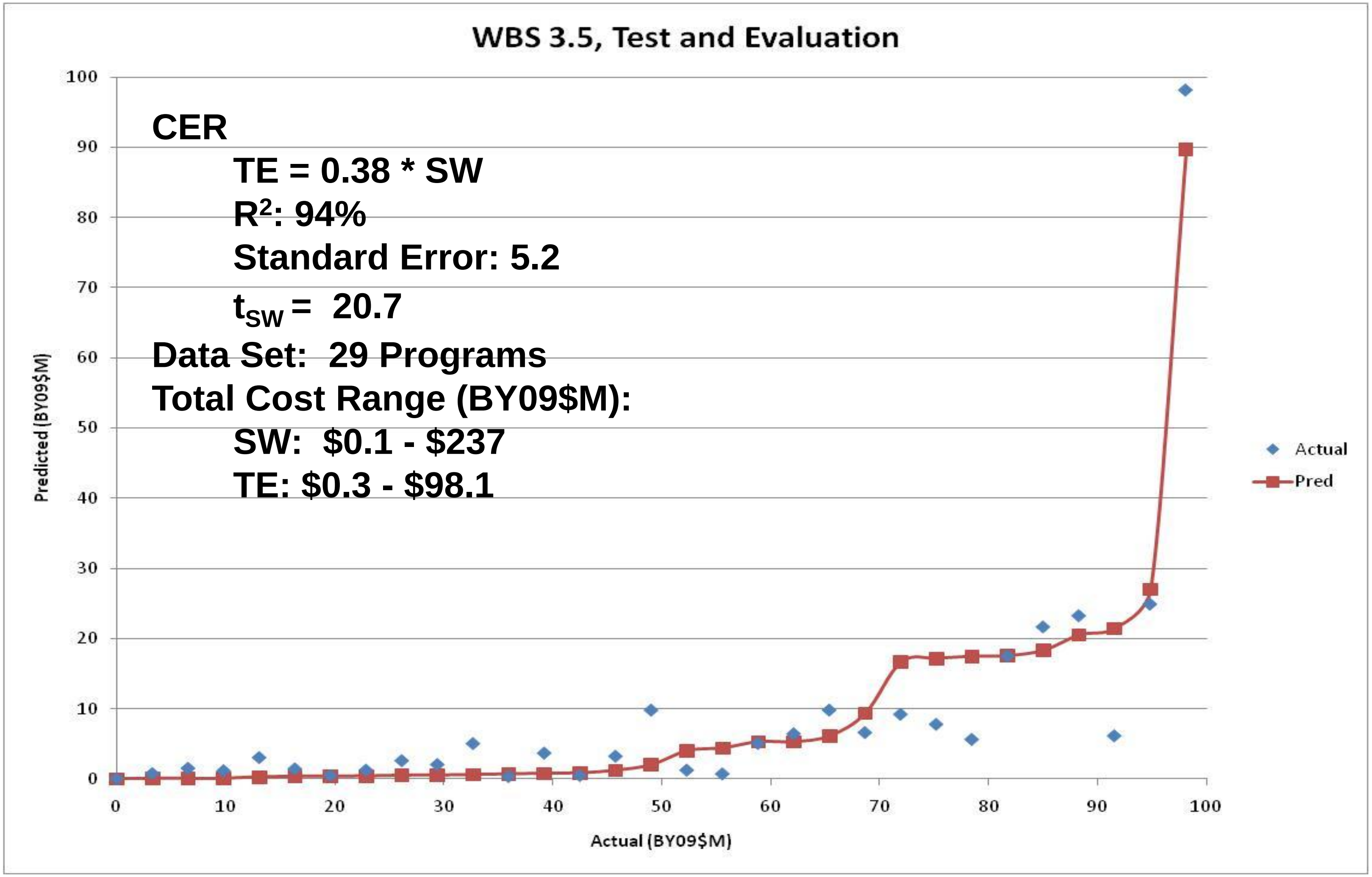
Actual vs. Predicted Chart
WBS 3.5 Test and Evaluation



CER

TE = 0.38 * SW

R^2: 94%

Standard Error: 5.2

t_{SW} = 20.7

Data Set: 29 Programs

Total Cost Range (BY09$M):

SW: $0.1 - $237

TE: $0.3 - $98.1

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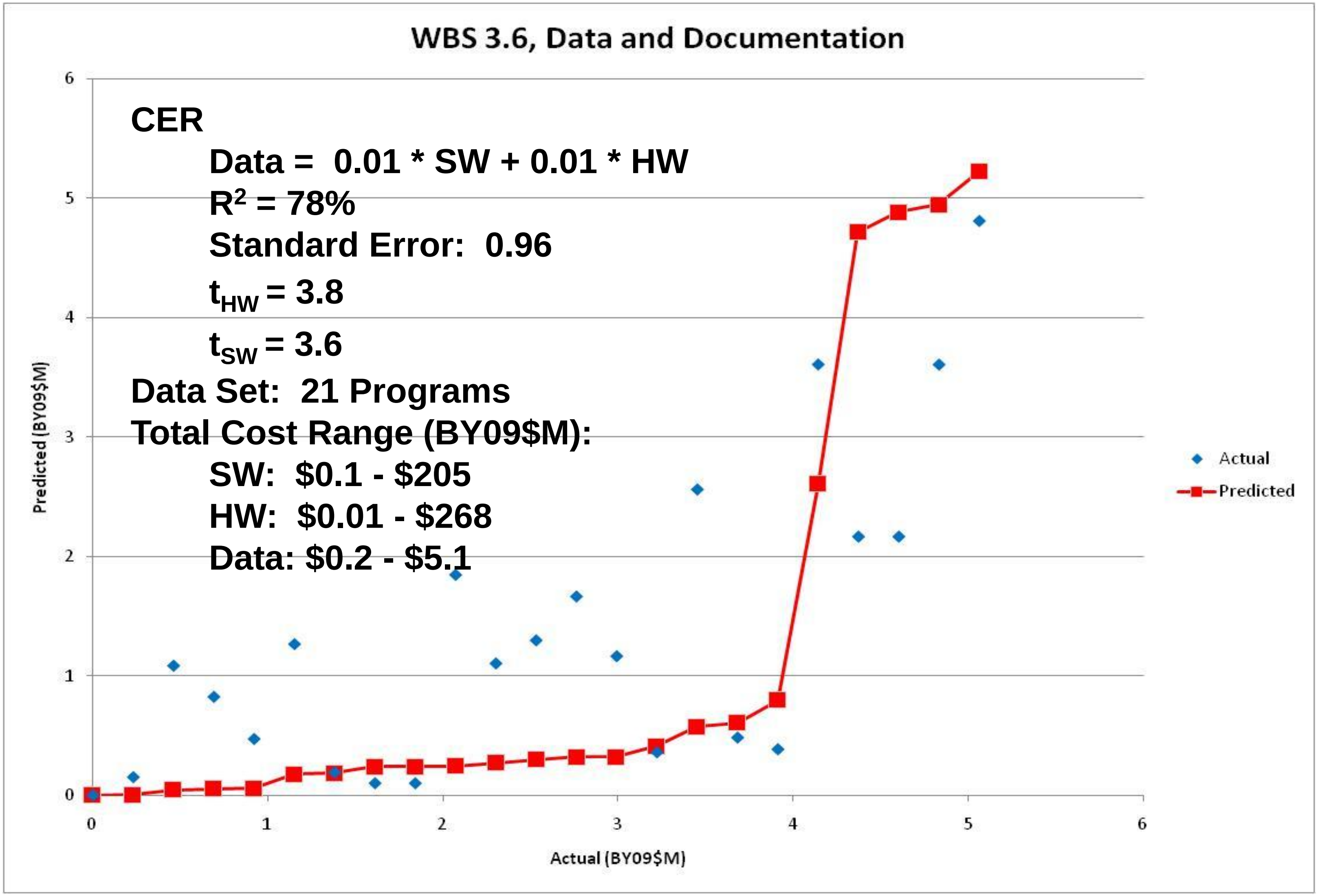
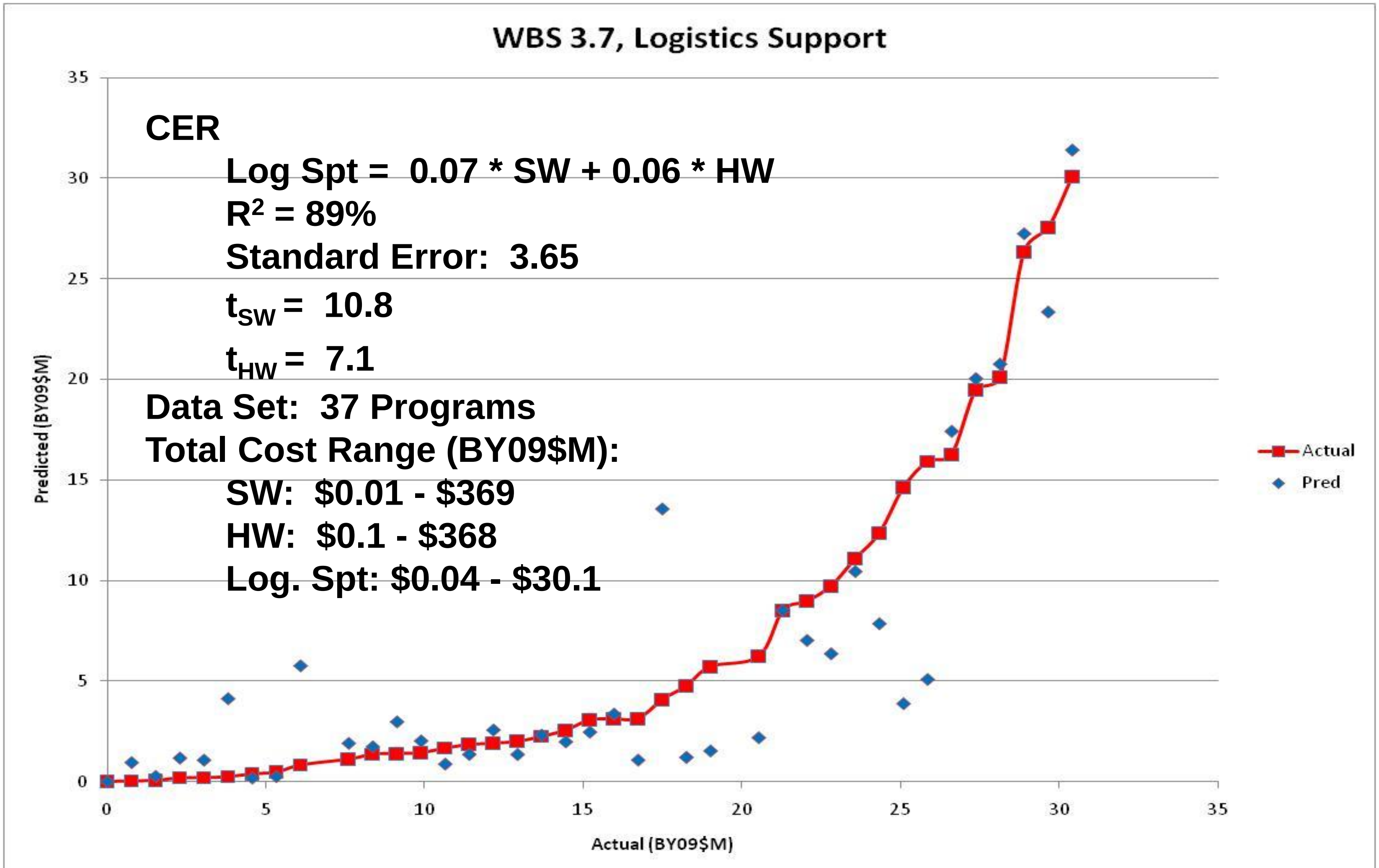
Actual vs. Predicted Chart
WBS 3.6 Data and Documentation



Actual vs. Predicted Chart
WBS 3.7 Logistics Support



CER

Log Spt = 0.07 * SW + 0.06 * HW

R^2 = 89%

Standard Error: 3.65

t_{SW} = 10.8

t_{HW} = 7.1

Data Set: 37 Programs

Total Cost Range (BY09$M):

SW: $0.01 - $369

HW: $0.1 - $368

Log. Spt: $0.04 - $30.1

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Improvement of CERs over Factors

- CER results were compared to old FAA Factors:
  - Generally, results of CERs are within the range of the Factors, giving statistical confidence to using these new CERs
  - Exception: CER result for WBS 3.6 Data is at the low range of its Factor result
- CERs are derived solely from baselined FAA Programs
  - Factors used a mix of DoD, Industry, and FAA sources
- CERs are statistically derived estimators
  - Factors are simple multipliers
- CERs use separate unique inputs for Hardware and Software
  - Factors use a single combined cost input

Wrap-Up

Conclusion – Replace outdated Factors with the new CERs for estimating certain WBS 3 software development, implementation, and management costs

Result – FAA will have more accurate and defendable cost estimates to support software investment decisions

Future – Follow-up actions are identified

Lessons Learned

– Reporting of & Availability of actual & baselined spending data provides the basis for future robust cost estimates

– The development of these Cost Estimating Relationships is an excellent example of using applied statistics in business, industry, and government

Acknowledgements

Gia Grady — FAA / IP&A
Al Clark — Galorath Associates

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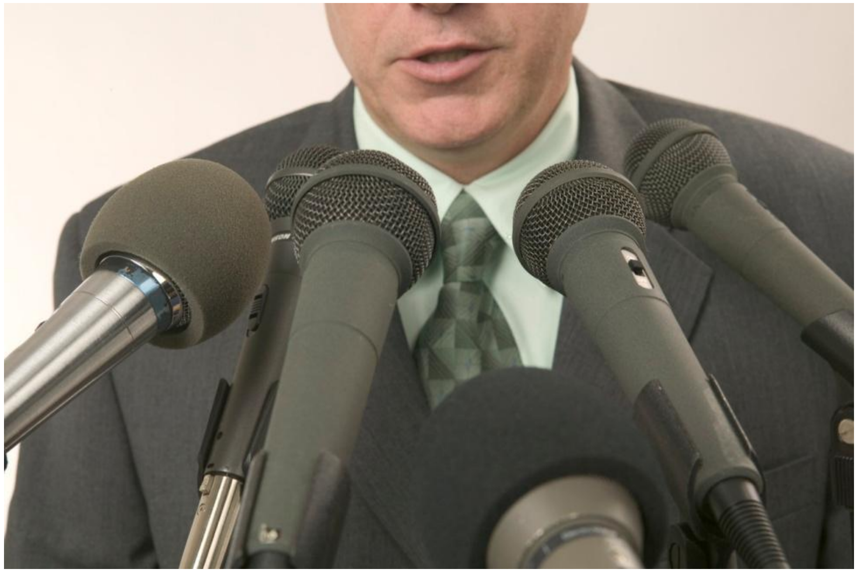

BACKUP SLIDES

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FAA WBS Version 4.1
(Elements with New CERs in Yellow)

	FAA Work Breakdown Structure
1	**Mission Analysis**
1.1	Identify Projected Demand for Services
1.2	Identify Technological Opportunities
1.3	Identify Projected Supply of Services
1.4	Mission Needs Analysis and Assessment
1.5	Initial Requirements Definition
2	**Investment Analysis**
2.1	Initial Investment Decision
2.1.1	Planning
2.1.2	Analysis
2.1.3	Documentation
2.2	Final Investment Decision
2.2.1	Planning
2.2.2	Analysis
2.2.3	Documentation
2.3	Rebaseline Decision
3	**Solution Development**
3.1	**Program Management**
3.1.1	Program Planning, Authorization, Management and Control
3.1.2	Contract and Grant Management
3.2	**System Engineering**
3.2.1	System Engineering Management
3.2.2	System Requirements and Definition
3.2.3	Analysis, design, and Integration
3.2.4	Value Engineering
3.2.5	Supportability, Maintainability, and Reliability Engineering
3.2.6	Quality Assurance Program
3.2.7	Configuration Management
3.2.8	Human Factors
3.2.9	Security
3.2.10	System Safety Engineering and Management
3.2.11	Other System Engineering Specialties
3.3	HW/SW Design, Development, Procurement, and Production
3.3.1	**Hardware Design and Development**
3.3.2	Software Design and Development
3.3.3	**HW/SW Integration, Assembly, Test and Checkout**
3.3.4	**Production Engineering**
3.3.5	Procurement/Production
3.4	**Physical and Airspace Infrastructure Dsgn and Devlpmnt**
3.4.1	Facility Planning and Design
3.4.2	Real Estate
3.4.3	Physical Infrastructure
3.4.4	Airspace Redesign
3.5	**Test and Evaluation**
3.5.1	System Development Test and Evaluation
3.5.2	System Operational Test and Evaluation
3.5.3	System Independent Software Verification and Validation
3.5.4	Independent Operational Test and Evaluation
3.6	**Data and Documentation**
3.7	**Logistics Support**
3.7.1	Logistics Support Planning
3.7.2	Test and Measurement Equipment Acquisition
3.7.3	Support and Handling Equipment Acquisition
3.7.4	Support Facilities Construction/Conversion/Expansion
3.7.5	Support Equipment Acquisition/Modification
3.7.6	Support Facilities and Equipment Maintenance
3.7.7	Initial Spares and Repair Parts Acquisition
3.7.8	Initial Training
4	**Implementation**
4.1	Program Management
4.1.1	Program Planning, Authorization, Management and Control
4.1.2	Contract Management
4.1.3	Human Resources Planning and Staffing
4.2	Engineering
4.3	Environmental and Occupational Safety and Health Compliance
4.4	Site Selection and Acquisition
4.5	Construction
4.6	Site Preparation, Installation, Test, and Checkout
4.7	Joint Acceptance Inspection/Commissioning/Closeout
4.7.1	NAS Charting and Aeronautical Information Management
4.8	Telecommunications
4.9	Implementation Training
5	**In-Service Management**
5.1	Preventive Maintenance/Certification
5.1.1	Preventive Maintenance/Certification
5.1.2	System Management Office (SMO) Overhead
5.1.3	FAA Academy Maintenance
5.2	Corrective Maintenance
5.2.1	Corrective Maintenance
5.2.2	System Management Office (SMO) Overhead
5.2.3	FAA Academy Maintenance
5.3	Modifications
5.4	Maintenance Control
5.5	Technical Teaming
5.5.1	Airway Transportation System Specialists Technical Teaming
5.5.2	Air Traffic Control Specialists Technical Teaming
5.5.3	Other Staff Technical Teaming
5.6	Watch Standing Coverage
5.7	Program Support
5.7.1	Program Planning, Authorization, Management and Control
5.7.2	Contract Management
5.8	Logistics
5.8.1	Supply Support
5.8.2	Replenishment Spares
5.8.3	Repair
5.8.4	Logistics Support Services
5.8.5	Support Equipment Maintenance
5.8.6	Technical Data
5.8.7	Maintenance Support Facilities
5.8.8	Commercial Depot Logistics Service (CDLS) Contracts
5.9	In-Service Training
5.9.1	Airway Transportation System Specialists In-Service Training
5.9.2	Air Traffic Control Specialists In-Service Training
5.10	Second Level Engineering
5.10.1	Program Management and Infrastructure Support
5.10.2	National Airspace System (NAS) Field Support and Restoration
5.10.3	Hardware and Software Engineering Support
5.10.4	Configuration Management
5.10.5	Process Improvement
5.10.6	Quality Assurance
5.10.7	Information System Security
5.10.8	Recurring NAS System Costs
5.10.9	Software Licenses
5.11	Infrastructure Support
5.11.1	Hazardous Materials Handling
5.11.2	Utilities, Building and Grounds Upkeep and Maintenance
5.11.3	Telecommunications
5.11.4	Building and Infrastructure Modernization and Improvements
5.11.5	Real Estate Management
5.11.6	Physical Security
5.12	NAS Charting and Aeronautical Information Management
5.13	System Performance Assessment
5.14	System Operations
5.15	Travel To And From Sites
6	**Disposition**
6.1	Program Management
6.2	Decommissioning
6.3	Engineering
6.4	Environmental Activities
6.5	Dismantle/Removal
6.6	Site Restoration/Closeout

Return - Factors Return - Overview Return - RPDs Return - Summary

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Characterization of Source RPD Data Sets

- By total number of usable RPDs:
  - Total number of RPDs obtained: 216 RPDs
  - With non-zero total cost: 208
  - With non-zero Hardware cost: 83
  - With non-zero Software cost: 76
  - With non-zero Software AND Hardware cost: 52
- Depending on CER hypothesis, maximum usable data sets range from 52 to 83 data points

- By number of RPDs with non-zero dependent variable values within applicable WBSs:
  - WBS 3.1 Program Management 116 RPDs
  - WBS 3.2 System Engineering 126
  - WBS 3.3.1 Hardware Design and Dev 65
  - WBS 3.3.3 HW/SW Integ, Assmbly, Test and Checkout 61
  - WBS 3.3.4 Production Engineering 33
  - WBS 3.4 Phys / Airspace Infrastructure Dsn / Dev 37
  - WBS 3.5 Test and Evaluation 83
  - WBS 3.6 Data and Documentation 58
  - WBS 3.7 Logistics Support 86
- Note that multiple RPDs contained non-zero dependent variable values but had zero values for one or both independent variables (i.e., Hardware and/or Software)

Return – Overview

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Approach for Development of Each CER

- Develop scatter plots of the data to observe outliers, relationships, and trends
- Determine availability of the two dependent variables
  - Software cost
  - Software schedule
- Determine candidate independent variables
  - Identify variables that can reasonably be size-estimated early in its Program life
  - Avoid using *SLOC* to estimate Program cost & schedule
  - Results will be correlated to 7 FAA domains, PM Staff Size, and Decision Duration (additional work pending)
- Develop hypotheses relating independent variables to dependent variables
  - H_0: IV is related to DVs by at least X% correlation
  - H_1: IV is not related to DV
- Transform selected data sets for development of non-linear CERs
- Calculate descriptive statistics (mean, standard deviation, coefficient of variation) to characterize the CER goodness-of-fit to the data
- Evaluate data set residuals and outliers
- Document the results

Return – Overview

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Typical Outliers and Rationale for non-Inclusion in CERs

	Ref	Program	Rationale
1	sheet76	ADS-B National Implementation Segment 1 and 2	Very low non-WBS 3.3, Hdw/SW Design costs
2	sheet143	ATO Strategy and Evalution	Very low non-WBS 3.3, Hdw/SW Design costs
3	sheet162	Augmentation for GPS - Wide Area Augmentation System (WAAS) LPV Segment	Most costs mapped into WBS 3.3.1, Hardware Design and Dev, not a Candidate Independent Variable
4	sheet115	Continued General Support - Airspace Management Lab - ATDP	Portion of Ops costs only - not complete program
5	Sheet1	En Route Automation Program - En Route Auto Mod (eRAM)	Extremely large program, beyond range of most data - does not fit trends derived from smaller programs
6	sheet199	FLEX - Separation Management Approach Precision Approaches: Continued Development. Define the concepts, simulations, etc.)	Planning portion of program only
7	sheet93	FLEX - Separation Management Arrivals - Access and Environment RNAV/RNP with 3D and required time of arrival	Very low non-WBS 3.3, Hdw/SW Design costs
8	Sheet41	HAATS	Very low non-WBS 3.3, Hdw/SW Design costs
9	Sheet17	Instrument Flight Procedures Automation (IFPA)	Very low non-WBS 3.3, Hdw/SW Design costs
10	sheet189	Juneau Airport Wind System (JAWS)	Very low WBS 3.3, Hdw/SW Design costs relative to total WBS 3, Solution Development, costs
11	sheet77	NAS Voice Switch	Very low WBS 3.3.2, Software, and 3.3.5, Hardware costs relative to total WBS 3, Solution Development costs
12	sheet141	National Airspace System Interference Detection, Locating, and Mitigation (NAS IDLM)	Several missing values for Dependent WBS Elements (e.g., T&E, Data, Logistics)
13	Sheet33	National Airspace System Recovery Communications (RCOM)	Very low non-WBS 3.3, Hdw/SW Design costs
14	sheet180	NEXRAD - Legacy, Icing, and Hail Algorithms	Algorithm development only - not complete program
15	sheet145	NextGen Trajectory-Based Operations (TBO)	Very low WBS 3.3, Hdw/SW Design costs relative to total WBS 3, Solution Development, costs
16	sheet181	Terminal Doppler Weather Radar (TDWR) - SLEP	SLEP - not complete development and implementation program
17	sheet182	Weather and Radar Processor (WARP) Sustain and Tech Refresh	Portion of Ops costs plut Tech Refresh - not complete program

Return - Approach

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SW and HW Costs Used to Develop CER Comparisons to Factors

- Methodology:
  - Low = Mean of SW and HW range from PM CER (-1 Standard Deviation would result in negative values)
  - Medium = Average of SW and HW range from PM CER
  - High = +1 Standard Deviation of Medium
- Using above cost ranges yields 6 alternatives of cost range parings:

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6
SW	$11.0	$ 11.0	$36.2	$ 36.2	$112.2	$112.2
HW	$29.7	$126.8	$29.7	$126.8	$ 29.7	$126.8

- *Continue* to next slide to see Results of CERs vs PEG comparisons -

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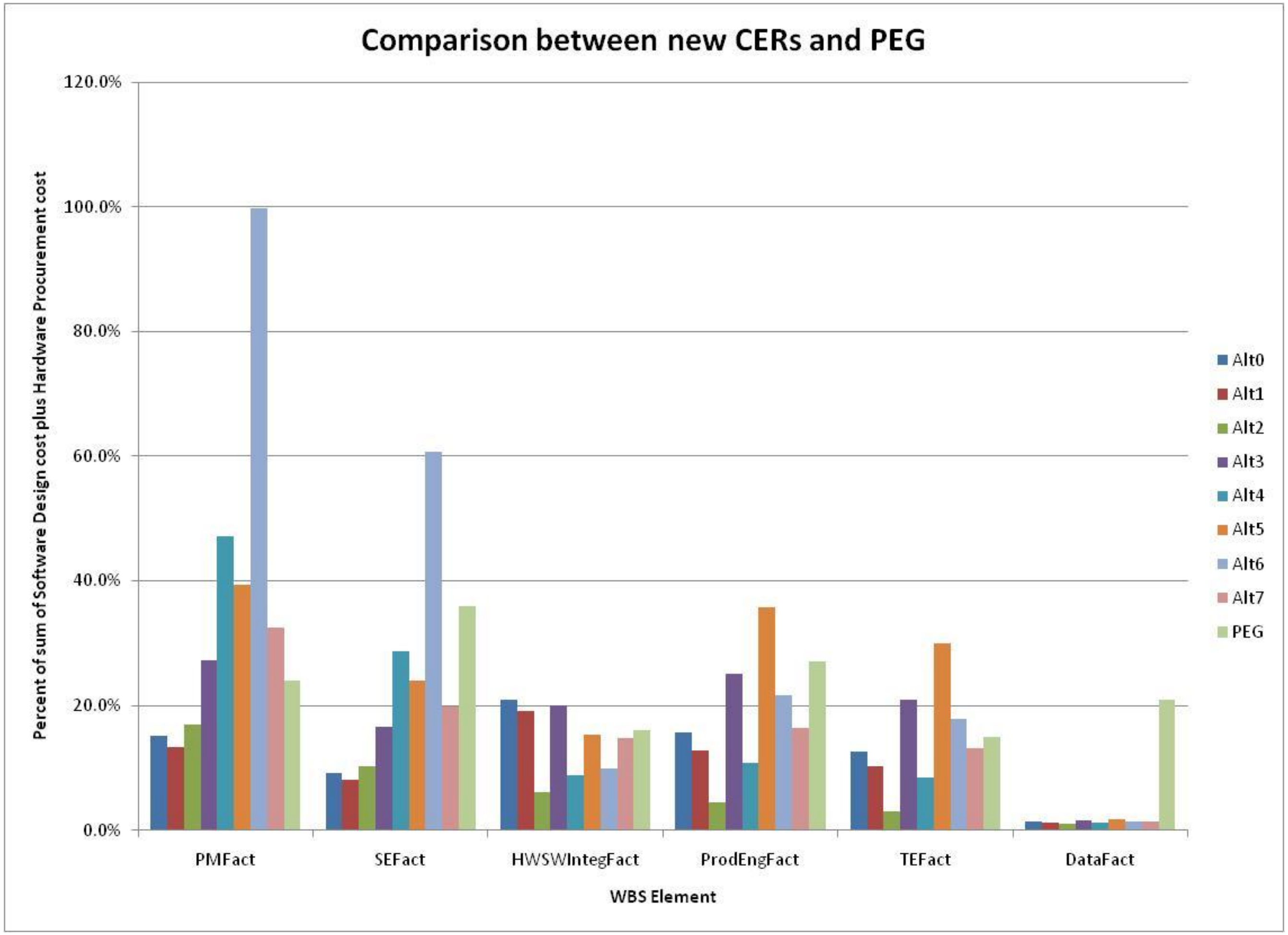
Comparison between new CERs and Factors



Return - Overview
Return - Improvement

Follow-on Actions

- Determine name for new set of CERs
  - PEG 2.0?
  - FAACER (FAA CER)?
  - Other?
- Maintain and expand existing RPD data base using SPIRE
- Expand EVM data collection effort
- Refine existing statistical relationships with expanded RPD data and/or appropriate EVM data
- Develop CERs for Software and Hardware
- Develop additional CERs for WBS Elements in:
  - WBS 4 Implementation, and
  - WBS 5 In-Service Management
  - Utilize new CERs to develop Rough Order of Magnitude (ROM) cost estimates for elements within WBS 3 Solution Development
- Map these 9 WBS elements to the new FAA WBS version 5 and re-evaluate the assumptions and re-calculate the CERs

Return – Wrap-up

EVM data for CER Validation

- Limited EVM data available for CER validation
  - EVM data are not representative of completed development and fielding efforts
  - EVM data are inadequate to develop robust CERs
    - Insufficient quantity
    - Not representative of typical FAA investments
- Due to these shortcomings, the new CERs were run against only some EVM data to investigate accuracy in predicting and comparing against this limited set of actual cost data

Return – Follow-on

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A mathematical classification of The Problem

(from the Abstract) "The determination of these CERs from using deductions about the data variables may be considered, from a purely mathematics perspective, as a **regularized ill-posed and ill-conditioned inverse modeling problem** in calculating the values of the CER parameters obtained from the planned budget (not actuals) data."

inverse modeling problem – A general framework that is used to convert observed measurements *(RPD budgeted costs)* into information about a physical object or system that we are interested in *(cost of software development)*. Inverse problems arise in many branches of science and mathematics, including statistical inference.

ill-posed – Problems that are not well-posed in the sense of Hadamard, i.e., mathematical models *(of deriving the CERs)* of physical phenomena *(the cost of developing the software)* should have the properties that (1) A solution exists, (2) The solution is unique, and (3) The solution depends continuously on the data. Inverse problems are often ill-posed and may suffer from numerical instability *(unpredictability)* when solved with errors in the data *(such as not using actual costs)*.

ill-conditioned – Even if a problem is well-posed, it may still be ill-conditioned, meaning that a small error in the initial data can result in much larger errors in the answers. The **condition number** of a function with respect to an argument measures the asymptotically worst case of how much the function *(the CER regression equation)* can change in proportion to small changes in the argument data *(the WBS budgeted costs)*. A problem with a low condition number is well-conditioned, while a problem with a high condition number is **ill-conditioned.**

regularized – Particularly in the field of inverse problems, regularization involves introducing additional information in order to solve an ill-posed problem. This information is usually of the form of a penalty for complexity. A theoretical justification for regularization is that it attempts to impose Occam's razor on the solution. From a Bayesian point of view, many regularization techniques correspond to imposing certain prior distributions *(normality)* on model parameters *(the WBS budgeted costs)*. The least-squares method *(yielding the CERs)* can be viewed as a simple form of regularization.

Return to Abstract

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Statistics 101

- **Non-linear least squares** is the form of least squares analysis which is used to fit a set of *m* observations with a model that is non-linear in *n* unknown parameters ($m > n$). It is used in some forms of non-linear regression. The basis of the method is to approximate the model by a linear one and to refine the parameters by successive iterations. There are many similarities to linear least squares, but also some significant differences

- The model function, *f*, in **LLSQ** (linear least squares) is a linear combination of parameters of the form The model may represent a straight line, a parabola or any other linear combination of functions. In NLLSQ (non-linear least squares) the parameters appear as functions, such as $\beta^2, e^{\beta x}$ and so forth. If the derivatives are either constant or depend only on the values of the independent variable, the model is linear in the parameters. Otherwise the model is non-linear.

- A ***t*-test** is any statistical hypothesis test in which the test statistic follows a Student's *t* distribution if the null hypothesis is supported. It is most commonly applied when the test statistic would follow a normal distribution if the value of a scaling term in the test statistic were known. When the scaling term is unknown and is replaced by an estimate based on the data, the test statistic (under certain conditions) follows a Student's *t* distribution.

Return – Reminder - OLS