It's All Rocket Science: On the Equivalence of Development Timelines for Aerospace and Nuclear Technologies

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Overview

- Introduction
- Using TRL for Technology Development Schedule Models
- The Equivalence of Development Timelines for Two Industries

Introduction

Acknowledgement and Notice

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The Problem

- Technology Development under high uncertainty, with increasing cost/schedule/maturity constraints.
- Even more challenging for government agencies:

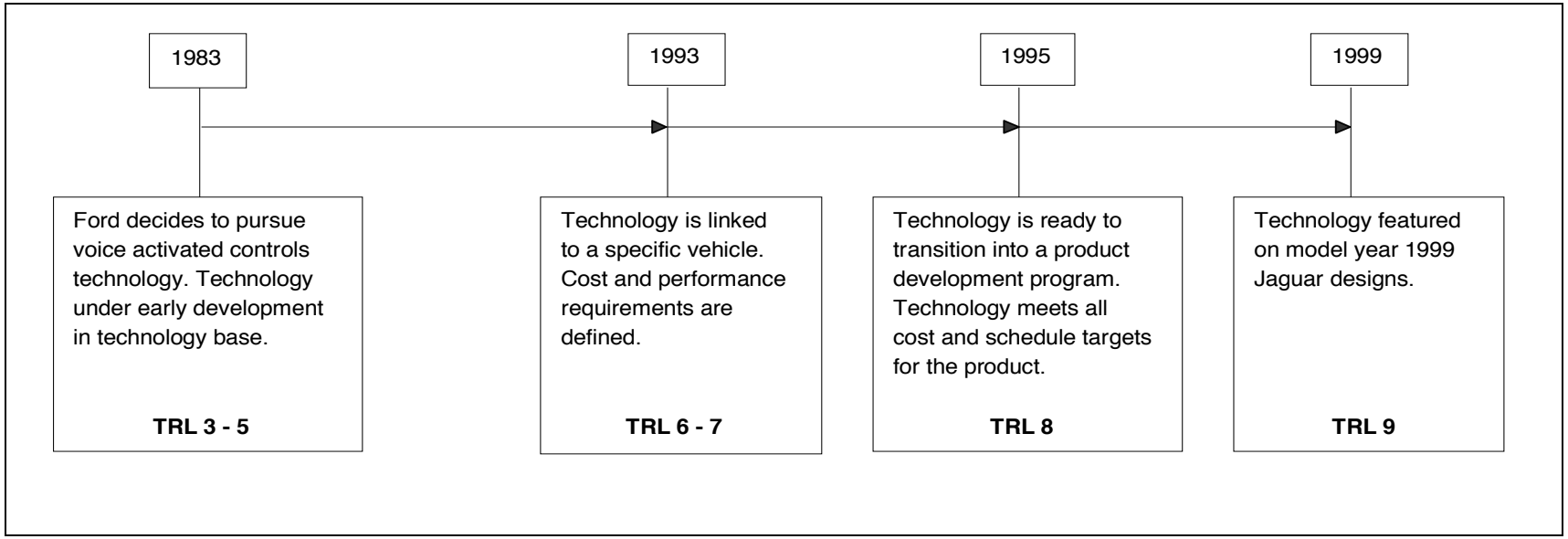
Technology Readiness Level Progression Example from GPS

US DoD R&D Budget Activity	TRL	Event Indicating Achievement of TRL	Cumulative Time to Reach TRL (yr)*
6.6 Operational Systems Development	9	Actual application "mission proven" through successful operations: GPS achieves full operational capability with full constellation of 24 Block II and Block IIA satellites.	22.7
6.4 Engineering and Manufacturing Development	8	Actual application completed and "mission qualified" through test and demonstration in an operational environment: DoD and Department of Transportation determines GPS system achieved the required assets available on orbit for initial operational capability.	21.4
6.4 Engineering and Manufacturing Development	7	Prototype demonstration in high-fidelity environment (parallel or shadow mode operation): Three GPS Block II satellites (required for triangulation) operational and tested with user equipment.	19.6
6.3b Demonstration and Validation	6	Prototype demonstration in a relevant end-to-end environment: GPS Block I satellite launched and tested with user equipment.	16.3
6.3a Advanced Technology Development	5	Module validation in relevant environment: Tests of GPS user equipment on simulated satellites.	14.1
6.2 Applied Research	4	Module validation in laboratory environment: successful research, development, and testing of initial Air Force and Navy satellites.	12.1
	3	Analytical and experimental critical function and/or characteristic proof-of-concept: TIMATION, the first three-dimensional space-based navigation system.	11.0
6.1 Basic Research	2	Technology concept and/or application formulated: TRANSIT, the first space-based navigation system.	6.0
	1	Basic principles observed and reported: Researchers at APL discovered that measurements of Doppler shift as Sputnik passed by were adequate to determine the entire satellite orbit. Frank McClure noted conversely, if the satellite orbit were known, position on the earth could be determined using these same Doppler measurements.	N/A

***Based on Smoker, R. and Smith, S. "Approach to Use of Selected Acquisition Reports for Measurement of TRLs and Associated System Cost Growth" 2008**

Technology Readiness Level Progression for Commercial Product

Figure 2.3: Time Line for Ford's Development of Voice Activated Controls Technology



Between 1993 and 1994, based on discussions with customers, Ford developed cost and performance requirements for the technology. Ford has

Page 28 GAO/NSIAD-99-162 Best Practices

16 years from TRL 3 to 9 comparable to 11.7 years for GPS

Research questions

- Using historical data, is it feasible to use TRL for technology development schedule models?

- If yes, can we use TRL data from multiple industries in the same model?

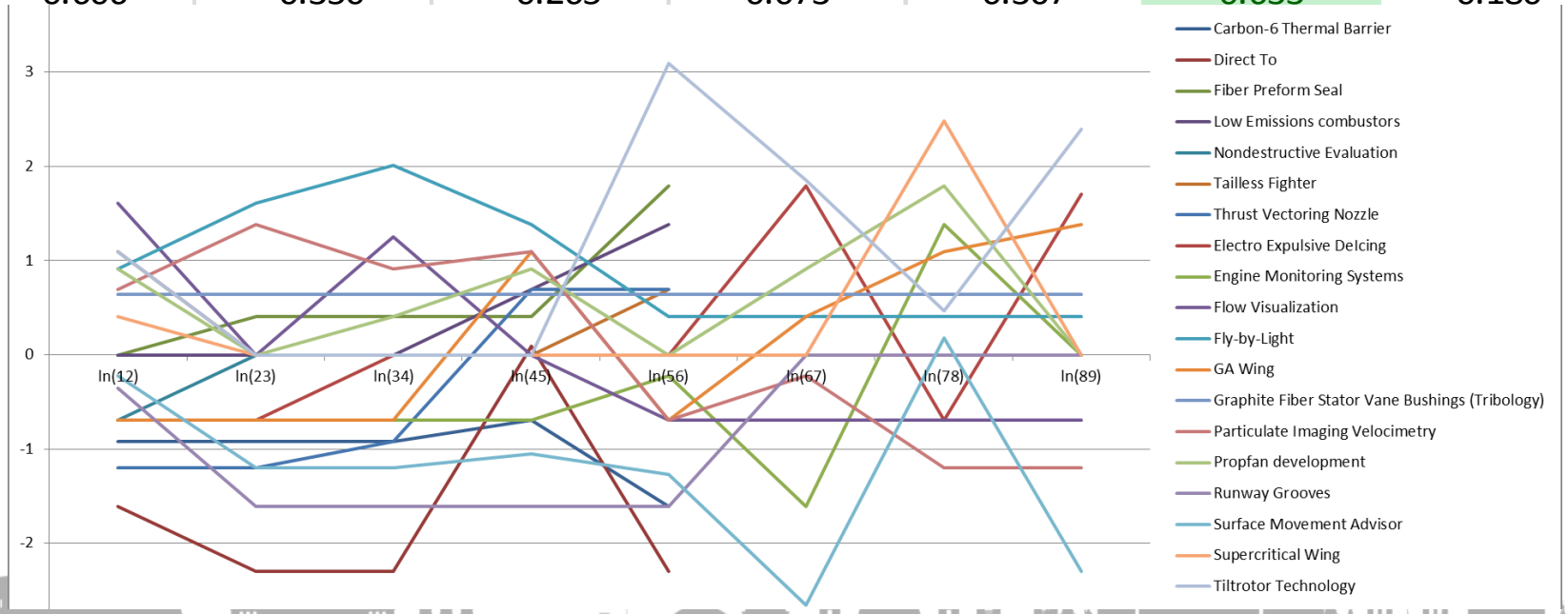
Using TRL for Technology Development Schedule Models

The NASA Dataset

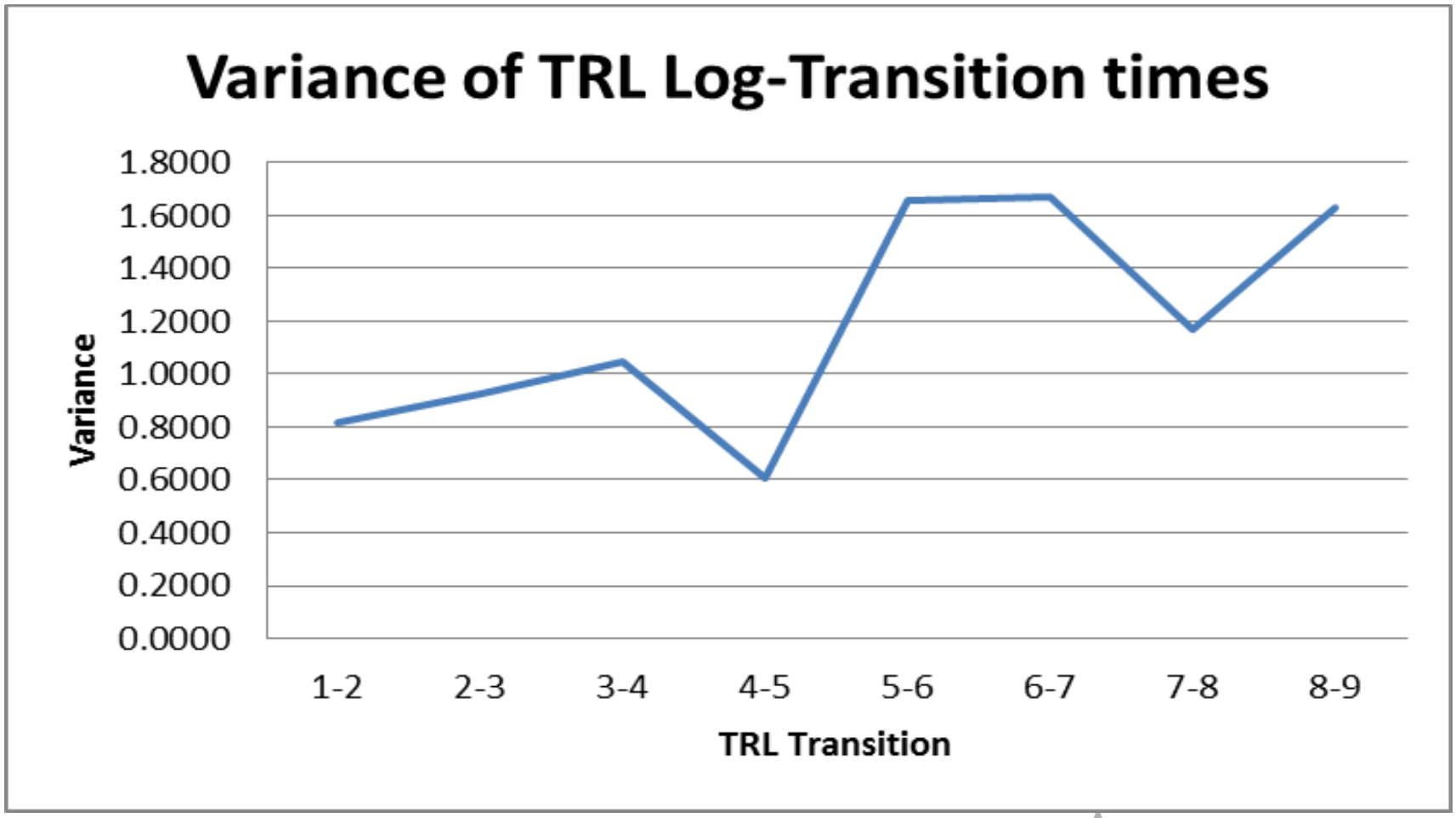
Transition	Carbon-6 Thermal Barrier	Direct To	Fiber Preform Seal	Low Emissions combustors	Nondestructive Evaluation	Tailless Fighter	Thrust Vectoring Nozzle	Electro Expulsive DeIcing	Engine Monitoring Systems	Flow Visualization	Fly-by-Light	GA Wing	Graphite Fiber Stator Vane Bushings (Tribology)	Particulate Imaging Velocimetry	Propfan development	Runway Grooves	Surface Movement Advisor	Supercritical Wing	Tiltrotor Technology
12	0.4	0.2	1	1	0.5	3	0.3	0.5	0.5	5	2.5	0.5	1.9	2	2.5	0.7	0.8	1.5	3
23	0.4	0.1	1.5	1	1	1	0.3	0.5	0.5	1	5	0.5	1.9	4	1	0.2	0.3	1	1
34	0.4	0.1	1.5	1	1	1	0.4	1	0.5	3.5	7.5	0.5	1.9	2.5	1.5	0.2	0.3	1	1
45	0.5	1.1	1.5	2	1	1	2	1	0.5	1	4	3	1.9	3	2.5	0.2	0.35	1	1
56	0.2	0.1	6	4	1	2	2	1	1	0.5	1.5	0.5	1.9	0.5	1	0.2	0.35	1	22
67								6	0	0.5	1.5	1.5	1.9	0.8	2.5	1	0	1	8
78								0.5	5	0.5	1.5	3	1.9	0.3	6	1	1.2	12	0
89								5.5	0	0.5	1.5	4	1.9	0.3	1	1	0.1	1	11
Criteria A	4	3	4	4	1	2	2	2	2	2	2	1	4	4	4	3	3	1	2
Criteria B	1	0	1	1	0	1	1	1	0	1	1	1	0	1	1	1	1	0	1
Criteria C	2	3	3	3	2	6	6	3	2	3	1	3	3	3	1	2	1	3	3
Criteria D	0	0	1	1	1	1	1	0	0	0	1	0	0	0	1	0	1	0	1
Criteria E	0	0	0	1	1	1	1	1	0	1	0	1	0	1	1	1	0	1	1
Criteria F	0	0	0	0	1	0	1	0	1	1	1	1	0	1	1	1	1	1	1

Correlation Analysis of the NASA Dataset (log)

ln(12)	ln(23)	ln(34)	ln(45)	ln(56)	ln(67)	ln(78)
log data	log data	log data	log data	log data	log data	log data
1.000	0.660	0.752	0.312	0.149	-0.074	-0.135
0.660	1.000	0.905	0.673	0.385	0.043	-0.170
0.752	0.905	1.000	0.639	0.351	0.113	-0.256
0.312	0.673	0.639	1.000	0.490	0.344	0.006
0.149	0.385	0.351	0.490	1.000	0.325	0.331
-0.074	0.043	0.113	0.344	0.325	1.000	-0.092
-0.135	-0.170	-0.256	0.006	0.331	-0.092	1.000
-0.606	-0.350	-0.265	0.073	0.307	0.633	0.180



Increase in Schedule Uncertainty vs. TRL

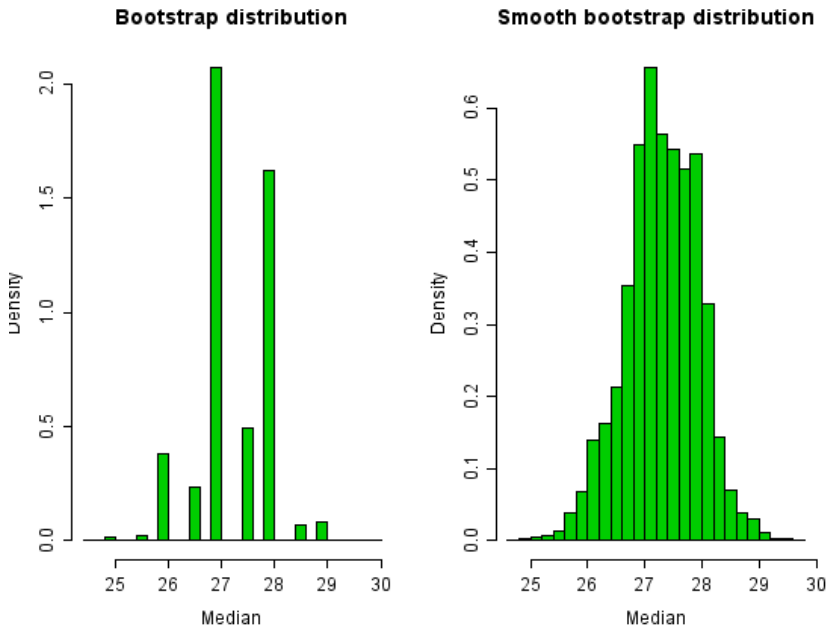


Forecasting Methods

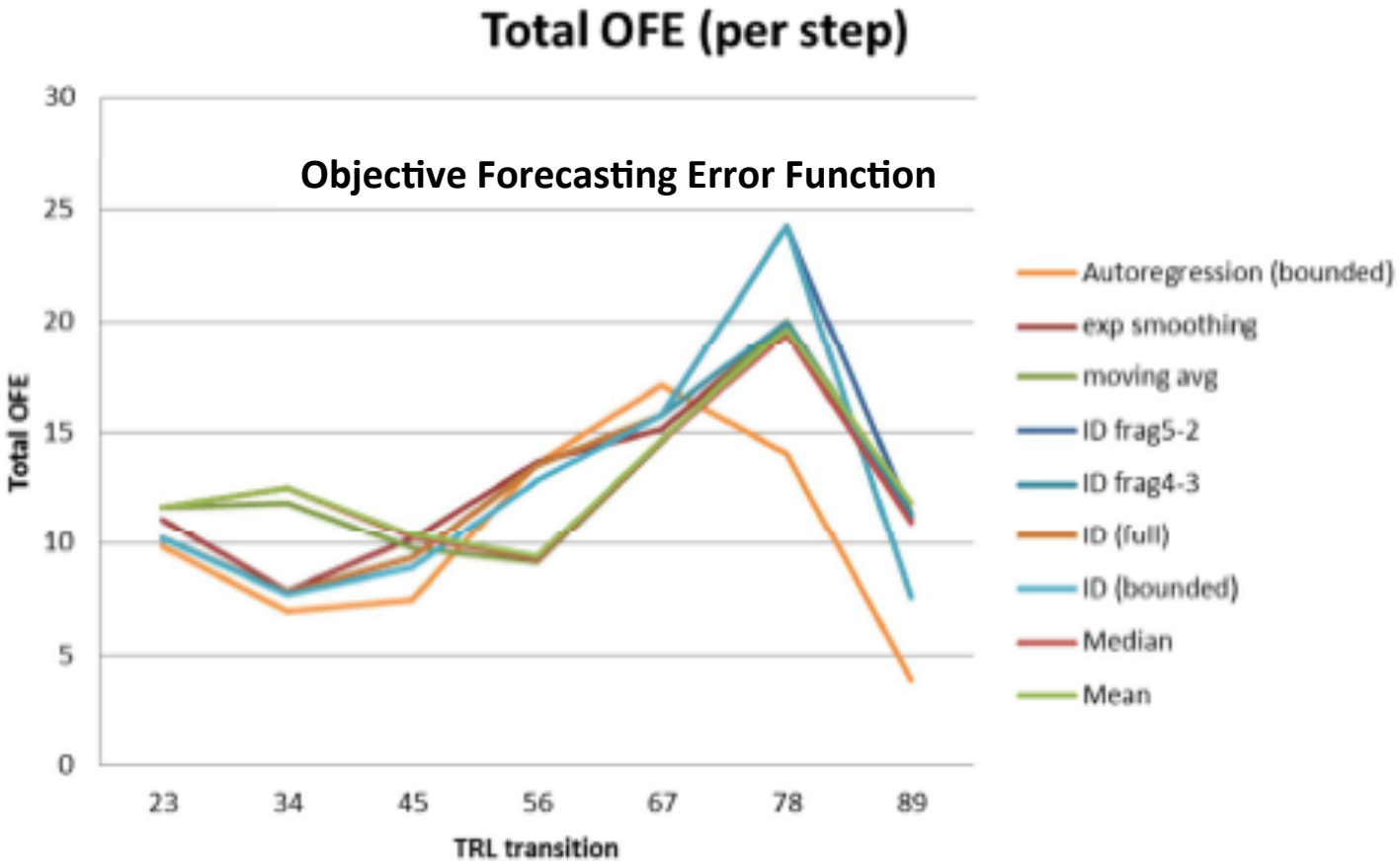
- Fixed Estimates
  - Mean
  - Median
  - Regression
- Influence Diagrams
  - ID (full)
  - ID (frag 4-3)
  - ID (frag 5-2)
  - ID bounded
- Extrapolation
  - Moving average
  - Exponential smoothing
  - Exponential smoothing with trend
- Regression
  - Full autoregression
  - Full autoregression (bounded)
- Other
  - Closest neighbor

Bootstrapping Used to Generate Median

- Iterated smoothed bootstrapping
- *Iterated*: to eliminate bias
- *Smoothed*: to look nice for the program managers

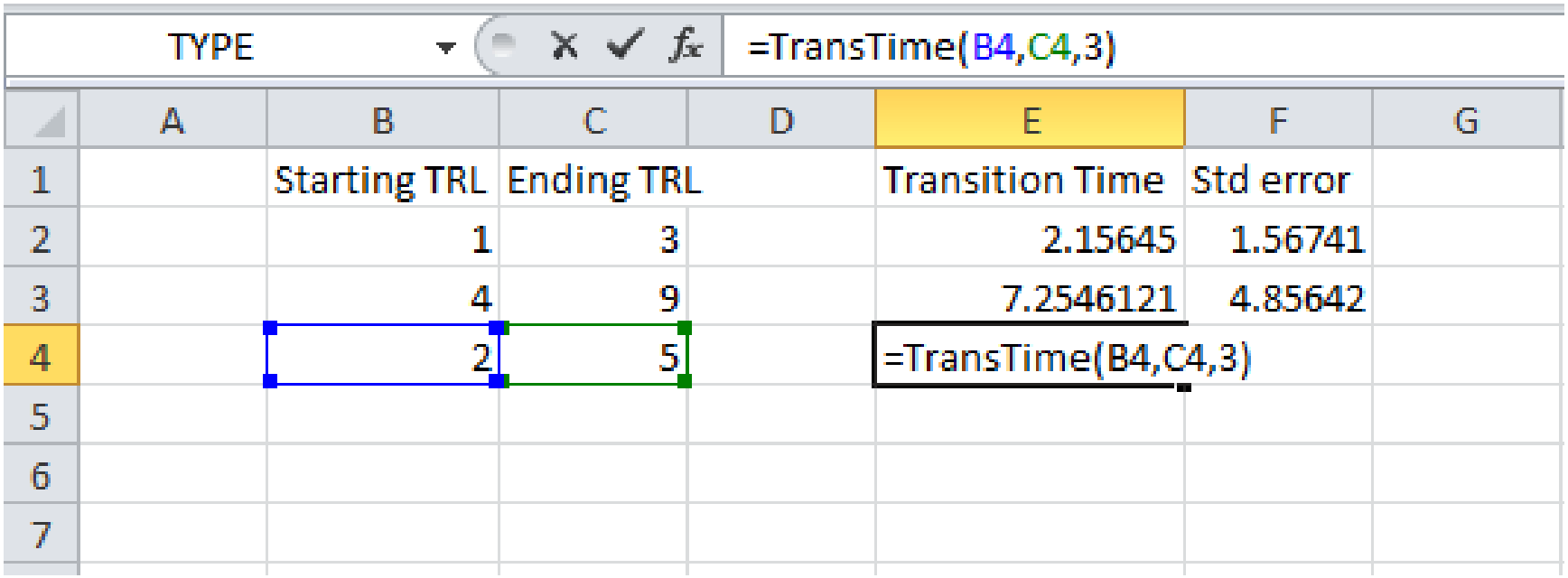


Forecasting results



- Some “smart” methods performed better than fixed estimates both in total error and in robustness
- Smart models might have “overlearned” this particular dataset

Excel Function Developed for Analysts



The Equivalence of Development Timelines for Two Industries

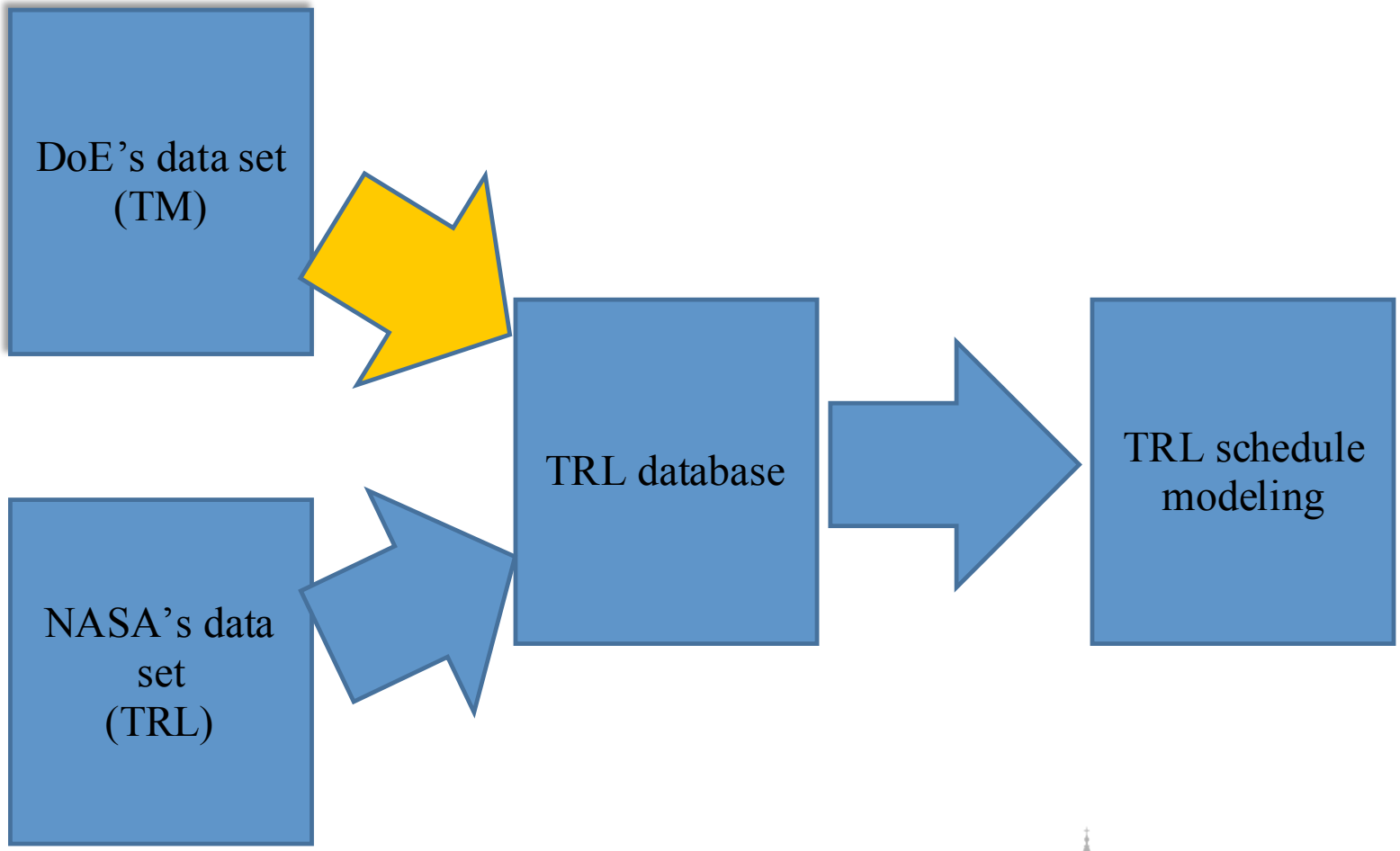
It's All Rocket Science

The Situation and Some Questions

- The NASA dataset is quite small
- We have more data from DOE projects
- Technical Maturity (TM) was used on the DOE projects instead of TRL
- Can we map TM to recent definitions of TRL provided by DOE?
- Are DOE TRL's equivalent to NASA TRL's for schedule modeling purposes?

TRL	DoE TRL Definition	NASA TRL Definition
1	Basic principles observed and reported in white papers, industry literature, lab reports, etc. Scientific research without well-defined application.	Basic principles observed and reported
2	Technology concept and application formulated. Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation.	Technology concept and/or application formulated
3	Proof-of concept: Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory- scale to identify/screen potential viability in anticipated service.	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Technology or Component is tested at bench-scale to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	Component and/or breadboard validation in laboratory environment
5	Component demonstrated at experimental scale in relevant environment. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.	Component and/or breadboard validation in relevant environment
6	Components have been integrated into a subsystem and demonstrated at a pilot-scale in a relevant environment.	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	Subsystem integrated into a system for integrated engineering-scale demonstration in a relevant environment.	System prototype demonstration in a space environment
8	Integrated prototype of the system is demonstrated in its operational environment with the appropriate number and duration of tests and at the required levels of test rigor and quality assurance. Analyses, if used support extension of demonstration to all design conditions. Analysis methods verified. Technology issues resolved pending qualification (for nuclear application, if required). Demonstrated readiness for hot startup	Actual system completed and “flight qualified” through test and demonstration (ground or space)
9	The project is in final configuration tested and demonstrated in operational environment.	Actual system “flight proven” through successful mission operations

Merging the DoE TM Data into the TRL Database



TRL Data from NASA

Transition	Carbon-6 Thermal Barrier	Direct To	Fiber Preform Seal	Low Emissions combustors	Nondestructive Evaluation	Tailless Fighter	Thrust Vectoring Nozzle	Electro Expulsive DeIcing	Engine Monitoring Systems	Flow Visualization	Fly-by-Light	GA Wing	Graphite Fiber Stator Vane Bushings (Tribology)	Particulate Imaging Velocimetry	Propfan development	Runway Grooves	Surface Movement Advisor	Supercritical Wing	Tiltrotor Technology
12	0.4	0.2	1	1	0.5	3	0.3	0.5	0.5	5	2.5	0.5	1.9	2	2.5	0.7	0.8	1.5	3
23	0.4	0.1	1.5	1	1	1	0.3	0.5	0.5	1	5	0.5	1.9	4	1	0.2	0.3	1	1
34	0.4	0.1	1.5	1	1	1	0.4	1	0.5	3.5	7.5	0.5	1.9	2.5	1.5	0.2	0.3	1	1
45	0.5	1.1	1.5	2	1	1	2	1	0.5	1	4	3	1.9	3	2.5	0.2	0.35	1	1
56	0.2	0.1	6	4	1	2	2	1	1	0.5	1.5	0.5	1.9	0.5	1	0.2	0.35	1	22
67								6	0	0.5	1.5	1.5	1.9	0.8	2.5	1	0	1	8
78								0.5	5	0.5	1.5	3	1.9	0.3	6	1	1.2	12	0
89								5.5	0	0.5	1.5	4	1.9	0.3	1	1	0.1	1	11

Scales for Determining Technical Maturity

Level	Hardware equipment maturity (EQ)	Facility readiness (FAC)	Safety readiness (SAFT)	Process Maturity (PM)
10	Equipment requirements not yet defined.	None available. New facility required.	New facility or facility restart required.	No currently identified solutions meet requirements
9	New design. Conceptual design completed.		NEPA process complete.	Design concept /technology application formulated
8	Experimental system. Cold demonstrated.			Cold feasibility demonstrated
7		Facility available. Major modifications required (new glove boxes, seismic mods).	Contractor Operational Readiness Review (ORR) complete.	
6	Experimental system. Hot demonstrated.			Hot feasibility demonstrated
5	Commercially equipment available. Requires modification.	Facility available. Moderate modifications required (modify glove boxes and equipment).	Contractor Readiness Assessment (RA) complete.	End-to-end design (flowsheet) complete
4	Integrated end-to-end equipment designs completed.			Cold prototype demonstrated at-end-use site
3	Cold prototype demonstrated.	Facility available. Minor modifications required (existing glove boxes and minor equipment mods).	DOE ORR complete (awaiting Secretary of Energy signature).	
2			DOE RA complete (awaiting Site Manager signature).	Hot prototype demonstrated at end-use site
1	Hot prototype demonstrated.			
0	Equipment in use processing the given material.	Facility operating. No modifications required.	Facility Authority to Proceed issued or within authorization basis.	Process integrated into operations

***Based on Kenley, C.R. and Creque, T.R. "Predicting Technology Operational Availability Using Technical Maturity Assessment." *System Engineering*. 1999.**

DoE Technical Maturity Data

R&D Plan Technology	TM Evaluation Date	PM	EQ	FAC	SAFT	Years to Go	Date Operational
Bagless Transfer System - FB	Sep-91	4	3	0	0	2.00	Sep-93
Calciner with Full Batch TGA	Apr-94	6	0	0	5	3.76	Jan-98
Cementation	Sep-92	2	0	3	9	0.08	Oct-92
Charcoal Treatment	Sep-92	1	1	0	0	1.00	Sep-93
Digital Radiography	Sep-91	2	0	2	5	1.54	Mar-93
Electrolytic Decontamination	Sep-91	4	6	7	0	2.25	Dec-93
Electrolytic Decontamination	Sep-92	4	3	7	9	1.25	Dec-93
HB Phase II Solution Conversion	Aug-94	4	3	5	0	2.09	Sep-96
Nitric Acid Soluble Bags	Sep-91	5	1	3	3	2.08	Oct-93
Pipe Component	Sep-92	6	6	2	3	0.33	Jan-94
Polycube Pyrolysis	Jul-94	4	0	0	0	3.67	Mar-98
Precipitation - Magnesium Hydroxide	Sep-91	2	0	0	8	0.17	Nov-92
Precipitation - MgOH HAN	Jan-95	0	0	0	0	1.71	Sep-96
Pretreatment of RFETS SS&C - SRS	Sep-91	5	7	5	5	2.58	Apr-94
Pretreatment of RFETS SS&C - RFETS	Sep-92	2	1	5	5	1.58	Apr-94
Pu238 Storage Container - SRS/LANL	Sep-91	2	1	0	0	1.08	Oct-92
Pu239 Standard Container - RFETS	Sep-92	5	0	3	9	4.12	Oct-96
PuSPS - Packaging - RFETS	Sep-92	4	3	0	0	4.79	Jun-97
PuSPS - Packaging - LLNL	Apr-94	5	0	3	5	2.83	Feb-97
Pyrochemical Salt Oxidation	Sep-91	2	1	0	0	2.33	Jan-94
Scrub Alloy Processing	Sep-91	6	1	3	9	5.56	Mar-97
SS&C Stabilization	Sep-91	2	1	7	5	2.08	Oct-93
Thermal Stabilization - HAN	Apr-94	2	1	3	9	3.19	Jun-97
Thermal Stabilization - RFETS	Sep-91	2	4	3	9	1.37	Jan-93
Trapping of Uranium Hexafluoride	Sep-91	6	1	3	9	1.17	Nov-92
Vertical Calciner	Sep-91	8	8	5	7	4.00	Sep-95
Vertical Calciner	Sep-93	0	0	0	10	0.00	Sep-95

Correspondence between TRL, PM, and EQ

TM	EQ	PM	TRL	DoE TRL Definition
10	Equipment requirements not yet defined	No currently identified solutions meet requirements	1	Basic principles observed and reported in white papers, industry literature, lab reports, etc. Scientific research without well-defined application.
9	New design. Conceptual design completed.	Design concept / technology application formulated	2	Technology concept and application formulated. Issues related to performance identified. Issues related to technology concept have been identified. Paper studies indicate potentially viable system operation.
8	Experimental system. Cold demonstrated.	Cold feasibility demonstrated	3	Proof-of concept: Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory- scale to identify/screen potential viability in anticipated service.
6	Experimental system. Hot demonstrated.	Hot feasibility demonstrated	4	Technology or Component is tested at bench-scale to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.
5	Commercially equipment available. Requires modification.	End-to-end design (flowsheet) complete		
4	Integrated end-to-end equipment designs completed.	Cold Prototype demonstrated at end-use site	5	Component demonstrated at experimental scale in relevant environment. Components have been defined, acceptable technologies identified and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.
3	Cold prototype demonstrated			
2		Hot prototype demonstrated at end-use site	6	Components have been integrated into a subsystem and demonstrated at a pilot-scale in a relevant environment.
1	Hot prototype demonstrated.			
0	Equipment in use processing the given material.	Process integrated into operations	7	Subsystem integrated into a system for integrated engineering-scale demonstration in a relevant environment.

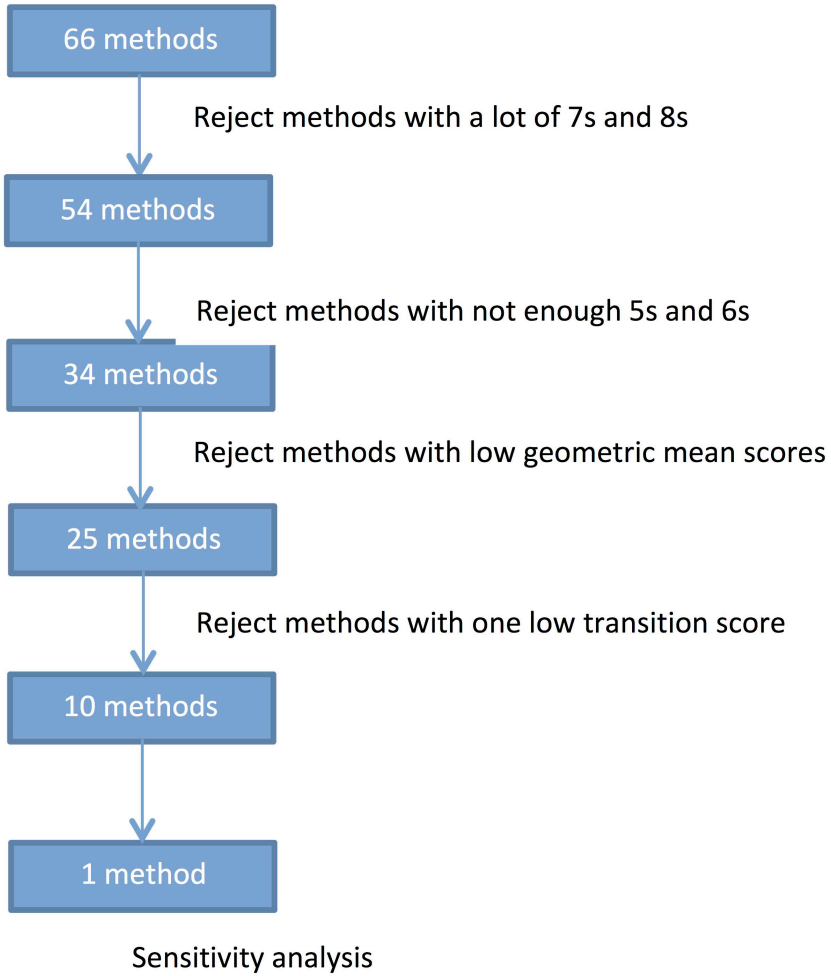
Example Correspondence Table for Mapping TM to TRL

TM	TRL
10	1
9	2
8	3
7	4
6	5
5	5
4	6
3	6
2	6
1	6
0	7

Methods Tested

Approach Mapping	Minimum and Maximum	Weighted Arithmetic Mean	Weighted Geometric Mean	Weighted Harmonic Mean	System Failure Approach
Ceiling		3;8;13;16	20;23	26;29	31
Floor		4;9;14;17	19;22	25;28	33
Round		5;10;15;18	21;24	27;30	32
Other	1;2;6;7;11;12				

Down-selecting To Find the Best Method



Sensitivity Analysis Results

Non-Log

	M1 Non-Log			M4 Non-Log			M18 Non-Log			M19 Non-Log			M25 Non-Log		
	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode
DoE-NASA / T 57	0,2037966	0,8680483	1,023260659	0,2832202	0,9813812	#VALUE!	0,3283842	0,9771305	1,303117919	0,1560792	0,9813812	0,823580499	0,1459566	0,9813812	0,973451859
DoE-NASA / M-W 57	0,2535563	0,9104338	0,557044969	0,2084497	1	0,954144976	0,2120284	0,9781417	0,838560602	0,1733676	1	0,442651784	0,1469011	1	0,828139827
DoE-NASA / Fisher ex. 57	0,2307692	1	0,421900643	0,2392939	0,9	0,622974688	0,1272727	0,7368421	0,967730105	0,2392939	1	0,426628587	0,2392939	1	0,962668358
DoE-NASA / T 67	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!
DoE-NASA / M-W 67	0,0930461	0,7656017	1,138347143	0,0723302	1	0,347546871	0,0924903	0,8798024	1,27014433	0,0638655	1	0,537124187	0,084994	1	0,836717677
DoE-NASA / Fisher ex. 67	0,0921246	0,8333333	0,502820504	0,068937	0,8333333	0,283515573	0,1490398	1	0,429379206	0,0657393	1	0,669392391	0,0921246	0,8333333	0,951322097
DoE-NASA / T GM	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!	n/a	n/a	#VALUE!
DoE-NASA / M-W GM	0,2356205	0,7715675	0,800335289	0,2033015	0,7347786	0,928464485	0,2272331	0,8066453	1,383330946	0,1957271	0,7314496	0,800670677	0,2004432	0,748979	1,34075057
DoE-NASA / Fisher ex. GM	0,2417927	0,9128709	0,671327934	0,2062015	0,7939191	0,508180998	0,1826317	0,7694837	0,791107031	0,1921201	0,9486833	0,595473771	0,213552	0,9128709	1,02755618

Log

	M1 Log			M4 Log			M18 Log			M25 Log			M32 Log		
	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode	5%	95%	Norm.mode
DoE-NASA / T 57	0,332498	0,9969882	0,80071283	0,1245221	0,9305906	1,154480839	0,1174343	0,8800382	0,708860578	0,0188269	0,9305906	#VALUE!	0,273028	0,9957346	1,287646519
DoE-NASA / M-W 57	0,2535563	0,9104338	0,557044969	0,2110157	1	0,957248125	0,2299602	0,9753959	0,861821388	0,1469011	1	0,907802955	0,2540932	1	1,012530978
DoE-NASA / Fisher ex. 57	0,2307692	1	0,421900643	0,2213622	0,9	0,606513779	0,1272727	0,7368421	0,967730105	0,2086957	1	0,850456603	0,2086957	0,7033818	0,832049206
DoE-NASA / T 67	0,696315	0,696315	#VALUE!	0,3509972	0,7206926	1,701017474	0,0444038	0,8734698	0,978597612	0,3509972	0,7206926	1,883482954	0,3509972	0,8108544	1,36750786
DoE-NASA / M-W 67	0,0930461	0,7656017	0,747626714	0,0723302	1	0,347546871	0,0924903	0,8512821	1,317884563	0,0846903	1	0,836440072	0,0723302	1	0,347546871
DoE-NASA / Fisher ex. 67	0,0921246	0,8333333	0,843739429	0,068937	0,8333333	0,283515573	0,1490398	1	0,429379206	0,0728016	0,8333333	0,927151593	0,068937	0,8333333	0,283515573
DoE-NASA / T GM	n/a	n/a	#VALUE!	0,3267211	0,6408733	2,43509352	0,1372803	0,828391	0,958250213	0,3267211	0,6478828	#VALUE!	0,3384723	0,76499	1,79357149
DoE-NASA / M-W GM	0,2356205	0,7715675	0,800335289	0,2033015	0,7347786	0,928464485	0,2200375	0,8015188	1,378408604	0,2004432	0,748979	1,403757051	0,2029139	0,7214199	0,951691228
DoE-NASA / Fisher ex. GM	0,2417927	0,9128709	0,671327934	0,2062015	0,7939191	0,508180998	0,1816207	0,7694837	0,789746494	0,2091613	0,9128709	0,978900182	0,2107628	0,7656053	0,538291346

Correspondence Table for Method 25

PM	TRL
10	1
9	2
8	3
7	4
6	4
5	4
4	5
3	5
2	5
1	6
0	7

EQ	TRL
10	1
9	2
8	3
7	4
6	4
5	4
4	5
3	5
2	5
1	6
0	7

Result of Applying Method 25 Correspondence Tables to Observed Data Points

		EQ										
		10	9	8	7	6	5	4	3	2	1	0
PM	10											
	9											
	8			3								
	7											
	6					4					4	5
	5				4						4	5
	4					4			5			5
	3											
	2							5			5	5
	1										6	
	0											6

P-values for Method 25

Transition 57

		T	M-W
DoE-NASA	0	0.813246	0.706485

	Chi^2	Fisher ex.
DoE-NASA	0.96042	0.732308

Transition 67

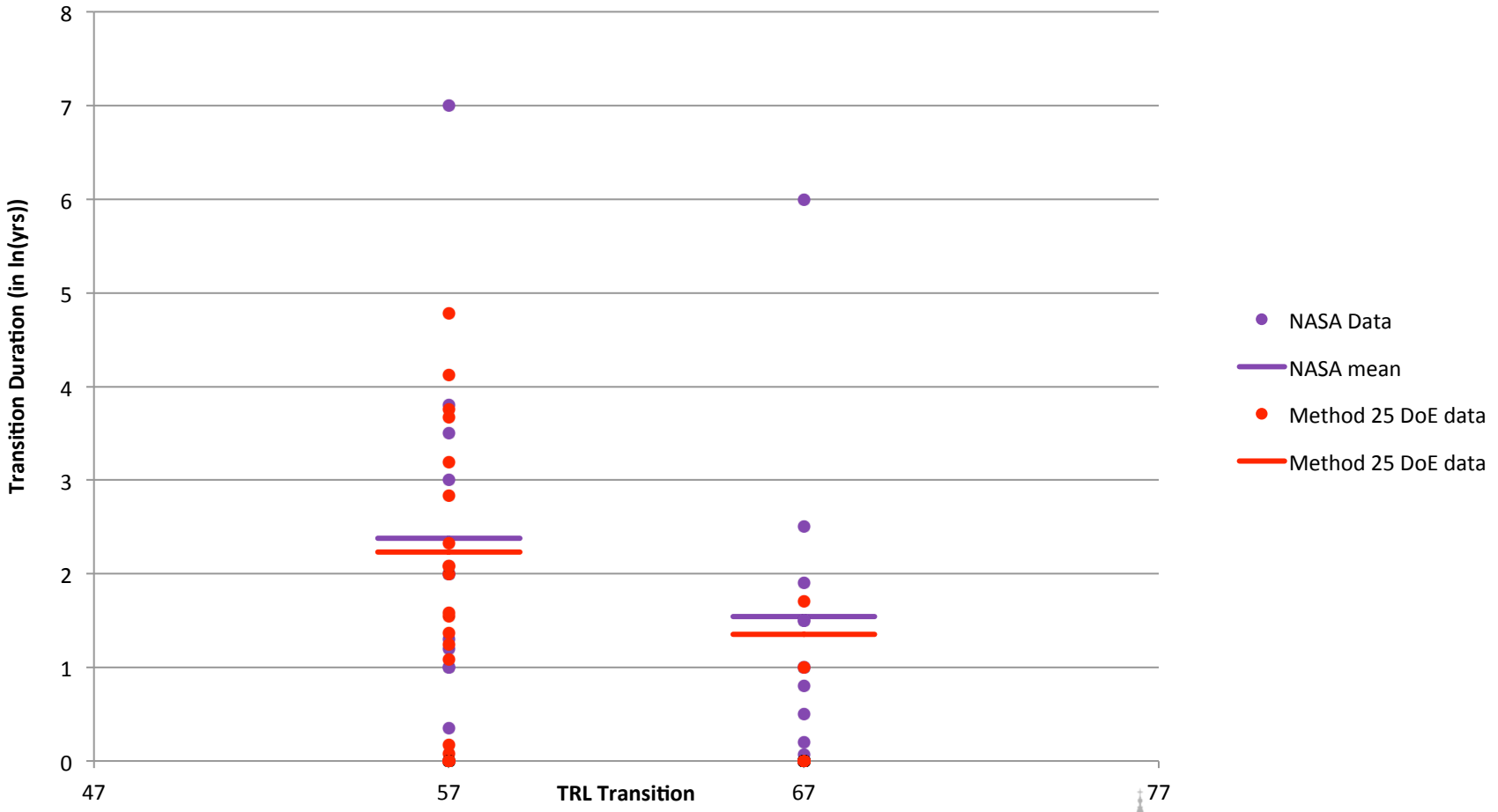
	T	M-W
0	0.878343	0.765602

Chi^2	Fisher ex.
0.512111	0.705128

Observed Transition Times Based on TRLs Derived Using Method 25

Transition	Bagless Transfer System - FB	Calciner with Full Batch TGA	Cementation	Charcoal Treatment	Digital Radiography	Electrolytic Decontamination	HB Phase II Solution Conversion	Nitric Acid Soluble Bags	Pipe Component	Polycube Pyrolysis	Precipitation - Magnesium Hydroxide	Precipitation - MgOH HAN	Pretreatment of RFETS SS&C - SRS	Pretreatment of RFETS SS&C - RFETS	Pu238 Storage Container - SRS/LANL	Pu239 Standard Container - RFETS	PuSPS - Packaging - RFETS	PuSPS - Packaging - LLNL	Pyrochemical Salt Oxidation	Scrub Alloy Processing	SS&C Stabilization	Thermal Stabilization - HAN	Thermal Stabilization - RFETS	Trapping of Uranium Hexafluoride	Vertical Calciner
12																									
23																									
34																									
45						1																			2
56	2	3.76	0.08		1.54	1.25	2.09	1.08	1.33	3.67	1.17		2.58	1.58	1.08	4.12	4.79	2.83	2.33	3.56	1.08	3.19	1.37	1.17	
67				1								1.71													0.92

NASA and Department of Energy Data Show Statistically Similar TRL Transition Times



The End

- Questions ?