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Method for Evaluating Bayesian Reliability Models for Developmental Testing (DT)

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Overview

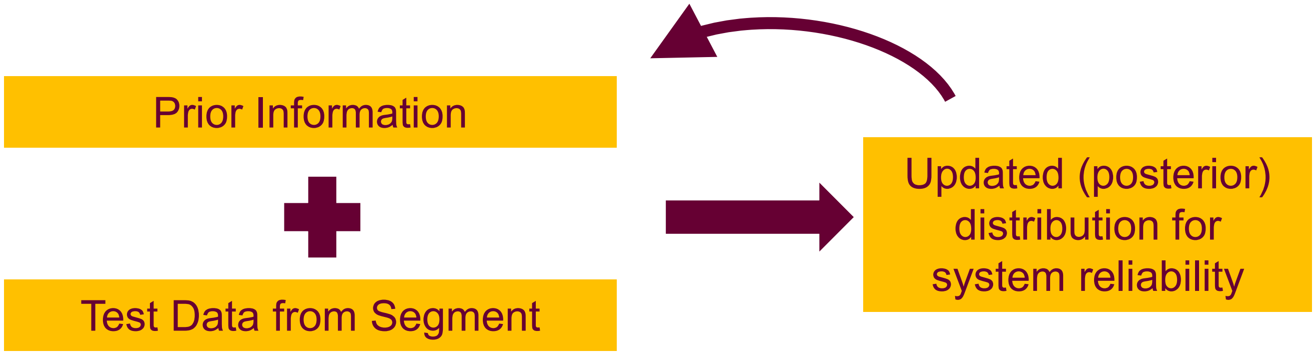
- **Current Frequentist Methods for Evaluating Reliability in DT Are Increasingly Challenged to Support Test Decisions**
  - **Tests are shorter and more complex**
- **Bayesian Models Can Help Address the Challenge, but There Is a Gap Between Potential and Actual Use**
- **This Research Is Designed to Help Overcome this Gap**
  - **The goal is a conceptual structure and best practices to facilitate analyst use of Bayesian models**
- **Thus, This Research Focuses on Application Without the Need to Create New Statistical Knowledge Per Se**
- **This Talk Is Structured in Two Parts**
  - **Motivating examples based on published methods**
  - **How to meet the goal**

Motivating Examples of Bayesian Methods for DT

- **Goals of this Section**
  - **Describe the way Bayesian methods include additional information in DT.**
  - **Illustrate the benefits of Bayesian methods for a generic system.**
    - **Apply Bayesian reliability planning and assessment methods from the literature to a notional system.**
    - **Compare Bayesian results to current frequentist results on simulated failure data.**
    - **Account for fix-effectiveness factor (FEF) uncertainty within the Bayesian paradigm**

- **Open-literature Bayesian Methods Used:**
  - **Assessment/Projection: Wayne and Modarres (2015)**
  - **Planning: Wayne (2018), Nation and Modarres (2019)**

Bayesian Methods Use Information More Effectively



- **Construct an Initial Prior Probability Distribution for System Reliability Using Information Available Before the Test Program Begins**

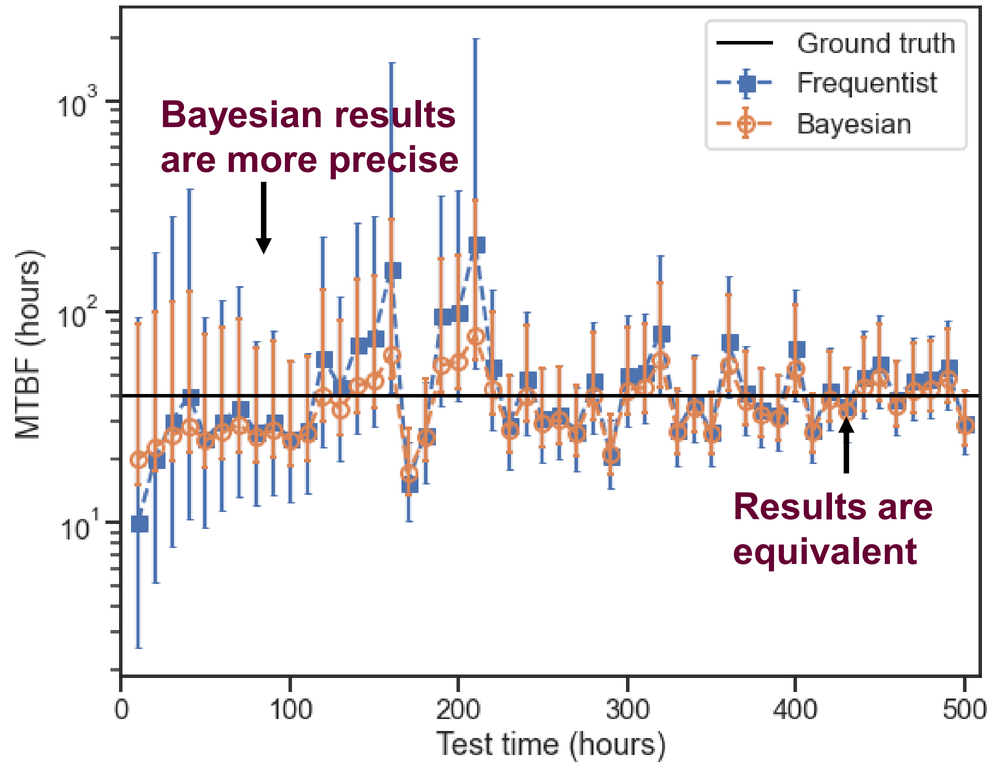
- **Combine the Prior With Test Data to Obtain an Updated Posterior Distribution for the System Reliability**

- **Use the Posterior Distribution as the Prior Distribution in a Subsequent Test Segment: Consistent Inclusion of Relevant Information Across the Test Program**

Improved Precision with Less Test Data

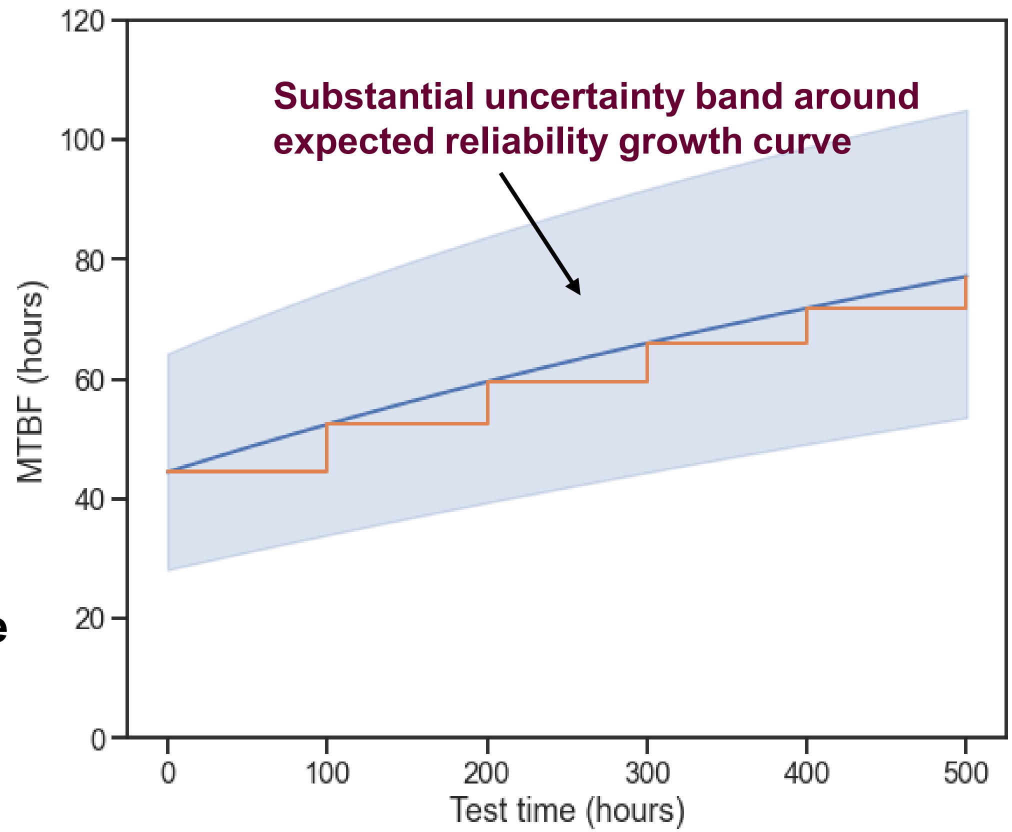
- **Results of Bayesian and frequentist methods applied to simulated data from a one-segment test**
  - **Ground truth MTBF = 40 hours.**
  - **Exponential distribution of system failures**
  - **Gamma prior for system failure rate (Wayne and Modarres 2015)**
- **Bayesian and frequentist error bars converge for long enough test segment.**
- **Inclusion of prior information in Bayesian method is especially advantageous for shorter test lengths**

Estimated MTBF vs segment length



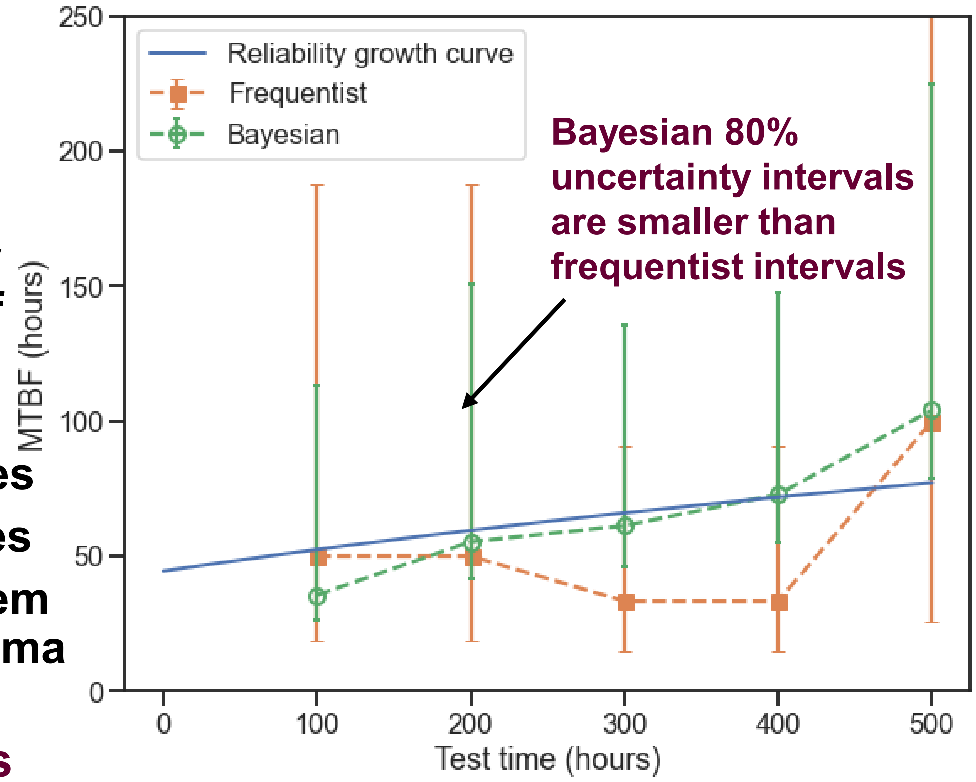
More Informative Test Plan – Adding Uncertainty to the Reliability Growth Curve

- **Reliability Growth Curve Calculated With the Method of Wayne (2018)**
  - **Notional series system with large number of failure modes.**
  - **Bayesian prior on system-level reliability: Gamma distribution for failure rate, MTBF in the range [19, 205] hours**
  - **Exponential likelihood for mode failures**
- **Model Predicts a Substantial Uncertainty Band Around the Reliability Growth Curve.**



Consistent Estimates in a Multi-Segment Test

- **Sampled System Failures Within Five 100-hour DT Segments.**
  - **Exponential distribution of failures**
  - **Failure rate set by the average reliability growth curve.**
- **Bayesian Point Estimates and Error Bars Calculated With the Method Of Wayne And Modarres (2015)**
  - **Gamma prior and posterior distributions for mode failure rates**
  - **Exponential distribution of failures**
  - **Posterior distribution of the system failure rate is approximately Gamma**
- **Bayesian Estimates are More Precise than Frequentist Estimates**
- **Clearer Trend in Bayesian Results**

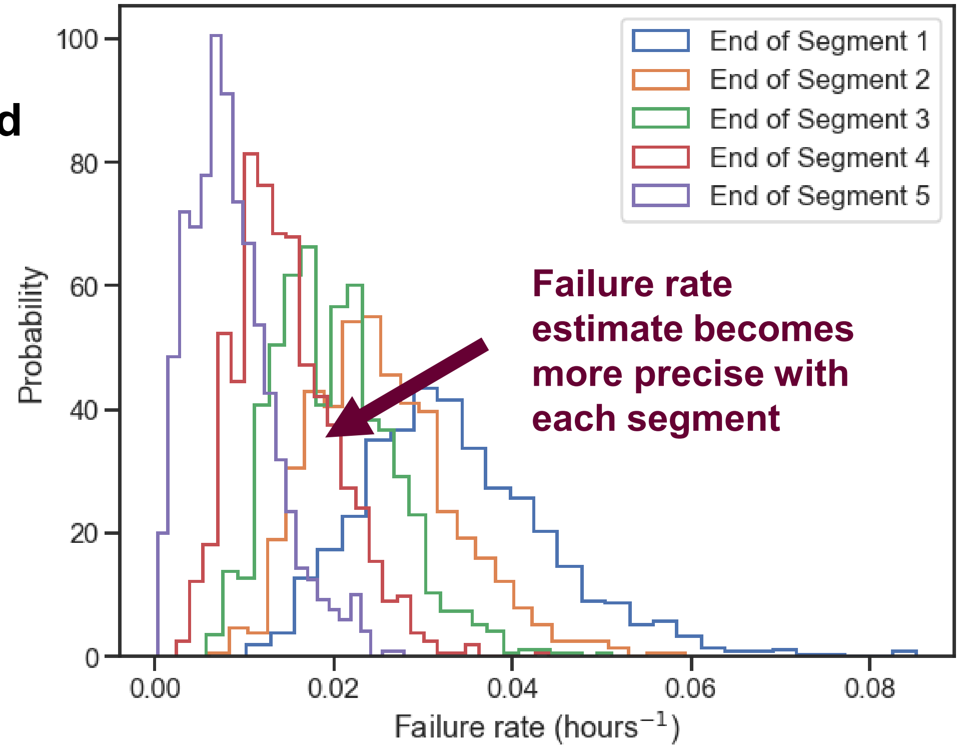


Accounting for Uncertain Fix Effectiveness in a Multi-Segment Test

- **Bayesian Methods Enable Inclusion of Fix-effectiveness Factor (FEF) Uncertainty.**
  - **Introduce a prior on the FEF applied at the end of first 4 segments**

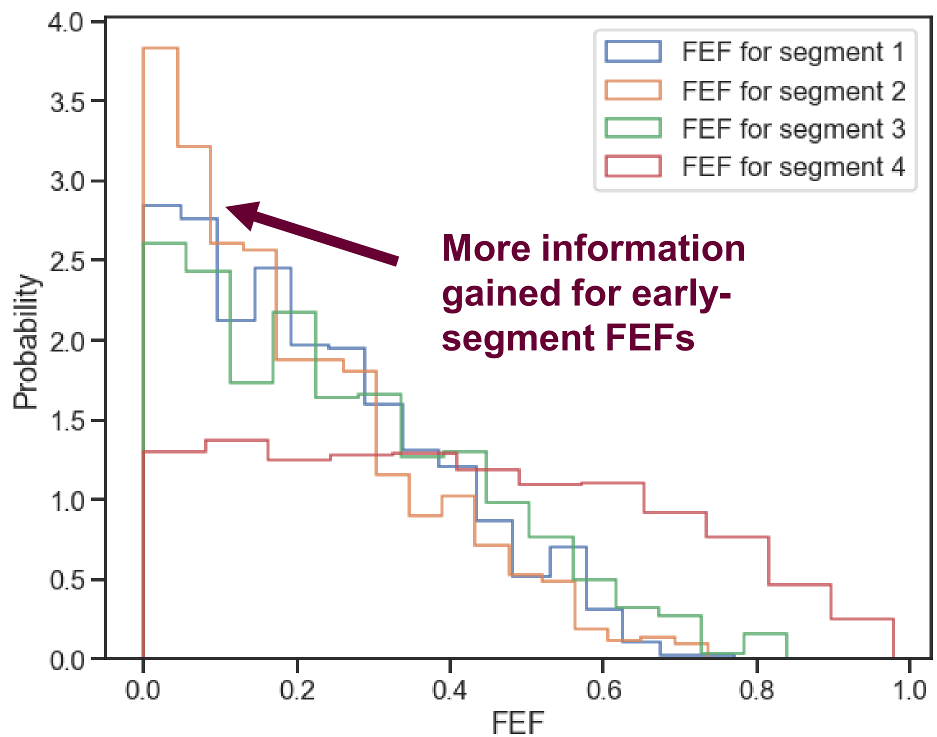
- **Sampled the Joint Posterior Distribution of the Initial System Failure Rate And FEFs with a Monte Carlo Method**
  - **Gamma prior on system failure rate**
  - **Uniform prior on FEFs**

- **Bayesian Posterior Distribution of The Failure Rate in Each Segment Narrows with Each Segment.**
  - **Results account for lack of precise knowledge of FEF values.**



Added Benefit: Estimate of FEF Uncertainty

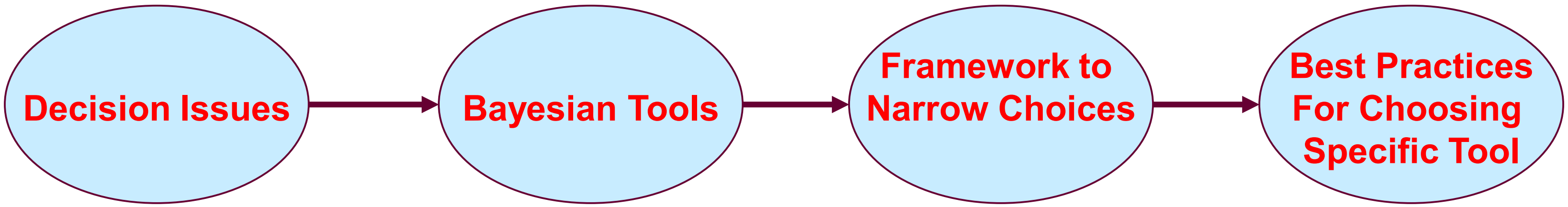
- **Can Calculate Marginal Bayesian Posterior Distributions on FEFs from Joint Posterior Distribution.**
- **More Information Has Been Gained for FEFs Applied After Earlier Segments**
  - **More change from uniform prior distribution observed in these cases**
- **Fixes After Early Segments Influence Performance in All Later Segments**
  - **More data available to the Bayesian method regarding these FEFs than later-segment FEFs**



Summary – The Example Bayesian Applications

- **Illustrated the Use of Prior Information and Combination of Information Across Test Segments**
- **In an Example With Notional Data, Provided More Precise Results in Both a Single Segment and a Multi-segment Context**
- **Enabled the Inclusion of Additional Sources of Uncertainty (e.g., FEF Uncertainty) in a Straightforward Way.**
- **Overall, Showed Ways that Bayesian Methods Can Improve Testers' Knowledge of System Reliability at Each Test Phase**

Framework and Best Practices



- **Articulate the DT Reliability Analyst's Problem**
  - **What are the decision issues that need analyst support ?**
  - **When are the decisions?**
- **Identify and Characterize Candidate Solutions**
  - **What relevant models exist?**
  - **What are model assumptions and data needs?**
- **Establish Framework for Selecting Candidate Solutions**
  - **Link Potential Solutions to decision Issues**
- **Articulate Best Practices for Applying the Framework**
  - **How to apply Framework to a specific developmental test program**

Defining the Problem

- **Overview Poll (Non-Attribution)**

Test Phase	DT Reliability Issue	Importance for Program Decisions				
		High	Moderate	Some	Little	None
Planning	Poorly supported initial reliability		X			
	Unreasonably High Program goal	X				
	Other (fill in):					
	Other (fill in):					
Execution	Timeliness				X	
	Lack of insight into unreliability source			X		
	Insufficient ability to determine operational reliability from developmental data					X
	Accurate probability to meet reliability requirement		X			
	Other (fill in):					
	Other (fill in):					

- **Interviews**
  - **More Depth on Poll Results**
    - **Additional issues**
    - **Reasons for ranking**
  - **More Information on Data Sources and Limitations**
    - **Contractor data**
    - **Government and contractor databases**

Identify and Characterize Candidate Solutions

- Literature Search
  - Model Types According To Test Phase
    - Reliability of complex systems
    - Test planning
    - Reliability tracking
    - Reliability projection

    Bayesian Counterparts to Traditional Statistical Models
  - Example Publication Sources
    - FFRDCs
    - Service test organizations
    - Professional journals

    FFRDC, Government, Academia
- Characterizing Solutions
  - Applicability
    - Issues addressed
    - Number and type of assumptions
  - Data Requirements
    - Types
    - Likely availability

  Potential for Match With Test Programs

Establish the Framework

Create Generic Evaluation Structure

DT Issue		Bayesian Model			
		Planning	Tracking	Projection	Complex System
Planning	Poorly Supported Initial Reliability	n/a			
	Unreasonably High Program Goal		n/a	n/a	
	Other	TBD	TBD	TBD	TBD
	Other	TBD	TBD	TBD	TBD
Execution	Unusably Great Confidence Intervals				
	Poor Insight Into Unreliability Sources	n/a	n/a	n/a	
	Insufficient Projection of Operational Reliability	n/a	n/a		n/a
	Accurate Probabiity to Meet Requirement				
	Other	TBD	TBD	TBD	TBD
	Other	TBD	TBD	TBD	TBD

- Assess How Well Each Type of Model Could Address Each Issue
- For Each Match, Determine How Well Data are Likely to be Available
- Combine the Information from the Above Two Steps to Grade Whether Each Type of Model Could Address Each Issue

Create Best Practices

Taylor Model Choice to Program Specifics

How Well Would Test Realities Fit Model Assumptions?

Prior-Program Tests
Contractor Tests
Test Item Instrumentation
Configuration Records
Configuration Control
Test Incident Reporting
Fix Schedule

→

Single or Combination of Systems
Prior Distribution
  Informative or Not
Likelihood Function
  Choice of Distribution

How Well Would Available Test Data Meet Model Data Needs?

Data from Prior Systems
Availability/Accessibility of Contractor Test Data
Timeliness of Failure Scoring
Timeliness of Failure Diagnoses

→

Ample Data Granularity
Data Consistency
In Time to Support Decision

Summary

- **Current Frequentist Methods for Evaluating Reliability in DT are Challenged to Support Decision Makers, but Bayesian Methods can Help**
- **For the DT reliability analysis, this research establishes a framework and best practices to facilitate the application of Bayesian Methods**
  - **Integrates considerations of test decision issues, test realities and Bayesian model needs**