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Estimating System Reliability from Heterogeneous Data

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Conference on Applied Statistics in Defense
October 21, 2015

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IDA

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Mission

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Reliability in a Defense and Security Context

Reliability : the ability of an item to perform **a required function**, under given **environmental** and **operating conditions** and for a stated **period of time**
(ISO 8402, International Standard: Quality Vocabulary, 1986)

***Operational mission* reliability**

- Most complex defense systems serve more than one required function (e.g., ships may provide transportation, defense, self-protection, etc.)
- Multiple operating environments: desert, littoral (close to shore), mountain, etc.
- Operating conditions vary depending on mission
- Mission requirements typically specify a fixed time period

Reliability in a Defense and Security Context

- **An additional consideration in operational mission reliability**
  - Diverse population of system operators: crew-caused failures are still failures in a defense context.

- **Concept of Operations – essential for defining operational mission reliability**
  - Defines standard mission length
  - Provides a breakdown of the expected activities during a mission
  - Can change over time as operational missions evolve

Motivating Example: Paladin Integrated Management (PIM)

- **The M109 Family of Vehicles (PIM) consists of two vehicles: the Self-Propelled Howitzers (SPH) and Carrier, Ammunition, Tracked (CAT) resupply vehicles.**
  - The M109 FoV SPH is the focus of this case study because of its two distinct functions. Additionally, the self-propelled 155 mm howitzer is designed to improve reliability over the legacy howitzer fleet.
- **PIM Mission - Field Artillery units employ the M109 FoV to destroy, defeat, or disrupt the enemy by providing integrated, massed, and precision indirect fire effects in support of maneuver units conducting unified land operations.**
  - In other words – must **move** with the unit and conduct fire missions **(shoot)**

PIM Operational Mission Reliability

System requirement

- Probability 0.75 of completing an 18-hour combat mission
- Standard translation using an exponential distribution is a mean time between system aborts of 62.6 hours:

$$\int_{18}^{\infty} \frac{1}{62.6} \exp\left(-\frac{t}{62.6}\right) dt = 0.75$$

- This translation is clearly too simple to use to drive our test planning.

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PIM Operational Mission Reliability

- **Concept of Operations: Operational Mode Summary/Mission Profile (OMS/MP)**
  - During early testing, an 18 hour-combat mission was specified as *drive 17.4 miles and shoot 223 rounds* (12.8 rounds/mile)
  - Prior to limited user (later, more operationally realistic) testing, the OMS/MP was updated to *drive 58.8 miles and shoot 104 rounds* (1.78 rounds/mile)

- **The requirement and OMS/MP highlight two issues**
  - How do we assess mission reliability?
  - How do we best measure PIM reliability for two distinct functions (driving and shooting)?
    - o Ultimately, how do we plan our sequence of tests?

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PIM Self Propelled Howitzer Data

- **Developmental testing focused on reliability from a driving and shooting perspective.**
  - Non-realistic "18 hour missions" completed over two days
  - Hours were not recorded
- **Limited user testing collected hours (and rounds and miles) data and testing was conducted in 18-hour mission cycles.**
- **Test-Fix-Test Approach**
- **Data limitations**
  - Usage rates are confounded with system changes
  - Developmental testing focused on rounds/miles
  - Different "realism" between tests

Test Phase	Vehicle	Number of Essential Function Failures	Cumulative Miles	Cumulative Hours	Cumulative Rounds fired	Ratio Rounds/Miles
Developmental Test 1	Vehicle 1	24	66.4		555	8.36
	Vehicle 2	21	67.3		445	6.61
Developmental Test 2	Vehicle 1	21	316.9		680	2.15
	Vehicle 2	22	254		743	2.93
Limited User Test	Vehicle 1	9	431.5	109.9	624	1.45
	Vehicle 2	16	432.6	112.8	623	1.44

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Questions of Interest

Mission activities may be appropriately measured with different metrics

- Different activities (moving, shooting, idling) may be best measured in different units (miles, rounds, hours)
- Motivated by PIM limited data problem, but useful in other complex systems

System versus Mission Reliability

- Mission reliability depends on the use of individual systems across operational missions
- For a given analysis, how do we quantify mission reliability taking into account the range of operational missions?
  - PIM focus on functions (miles driven, rounds fired) – could be extended to include environmental and operator considerations

Simulated Data

- As a starting point to address this problem, we simulated data based on the PIM reliability problem
- Simulated data allows us to answer the question for an “ideal” data collection case before addressing PIM’s data limitations

Mission	Mission Type	Miles	Rounds	Hours (Miles)	Hours (Rounds)	Hours (Idle)	Hours Total
1	Current OMS/MP	58.5	104	7.7	4.4	5.9	18
2	Mid Operational Tempo	38	164	5.0	7.0	6.0	18
3	Low Operational Tempo	17.4	104	2.3	4.4	11.3	18
4	High Operational Tempo	58.5	223	7.7	9.5	0.8	18
5	Original OMS/MP	17.4	223	2.3	9.5	6.2	18

Structuring the Problem

	Activity 1	**Activity 2**	**Activity 3**
Subsystem 1	$f_{11}(\lambda_{11k})$	$f_{12}(\lambda_{12k})$	$f_{13}(\lambda_{13k})$
Subsystem 2	$f_{21}(\lambda_{21k})$	$f_{22}(\lambda_{22k})$	$f_{23}(\lambda_{23k})$
Subsystem 3	$f_{31}(\lambda_{31k})$	$f_{32}(\lambda_{32k})$	$f_{33}(\lambda_{33k})$

Miles

Shots/Rounds

Hours

Simulated Data

- We simulated five missions, 138 total failures.
- All lifetime distributions are exponential
- Within each activity (move, shoot, idle), there are three subsystems (drive, gun, other) that might fail.
- We track miles, rounds, hours for each failure.
- Mission 4 (higher op-tempo) has failure rates multiplied by 1.5.

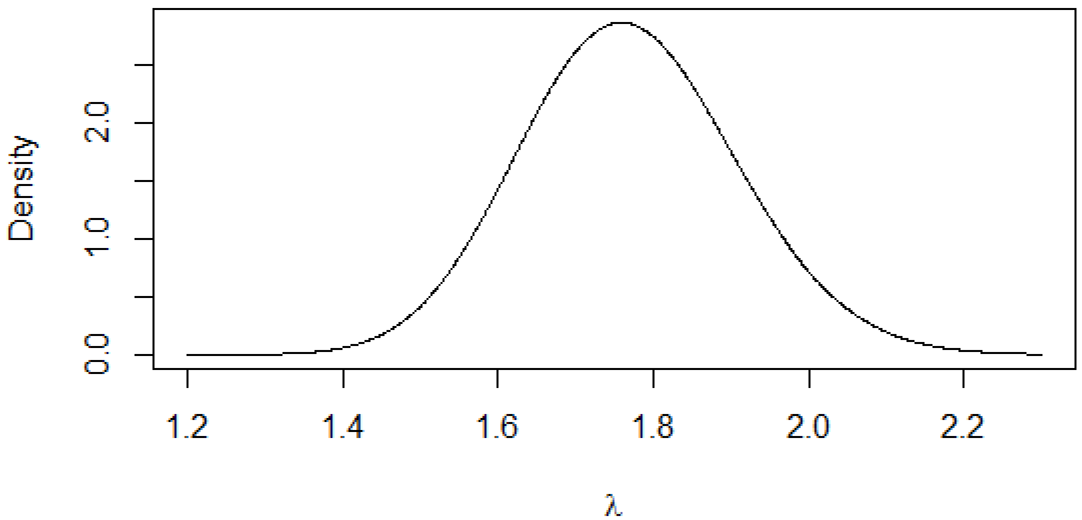
Approach

- Incorporating data from all phases of testing requires careful modeling.
  - Systems (hopefully!) experience reliability growth
  - Realism of testing changes
  - Operators change from test engineers to trained soldiers

- We have chosen a Bayesian approach for several reasons
  - We have the opportunity (need) to develop informative priors
  - Hierarchical modeling allows us to “borrow strength” across test vehicles

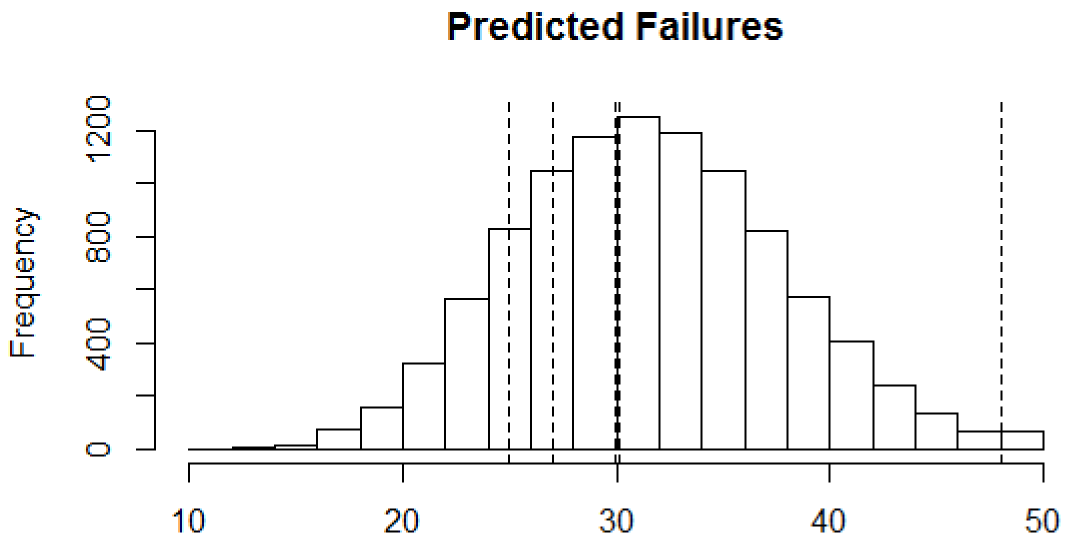
Model 1:
A Bayesian Version of the Standard DoD Solution

- $Y_k \sim$ Exponential(λ), $\lambda \sim$ Gamma(α,β)
- We may (must?) be able to develop an informative prior using data from previous tests.



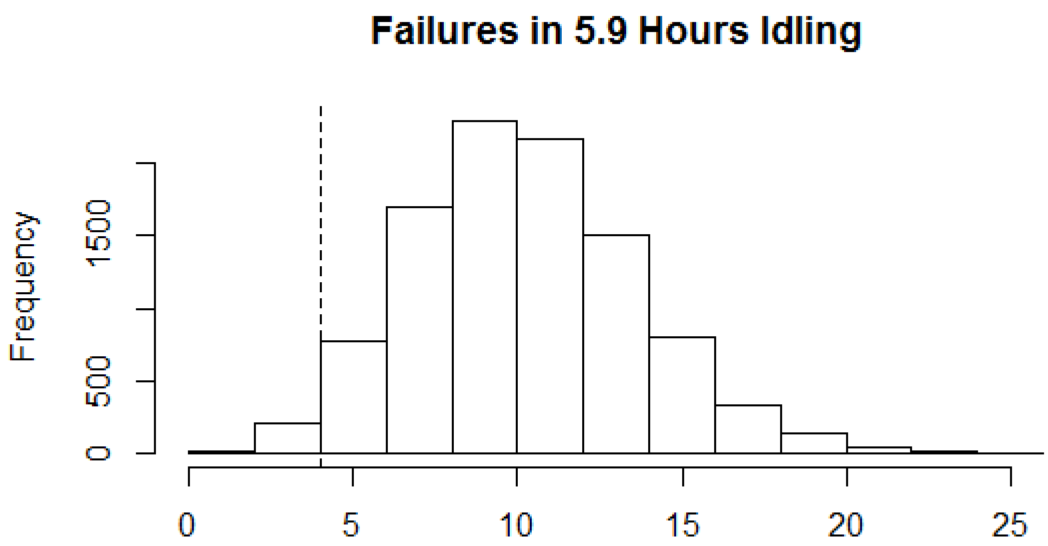
- Only possible for the “real” data in operational testing, since we need all observations in common units.

Model 1 Posterior Predictive Checks



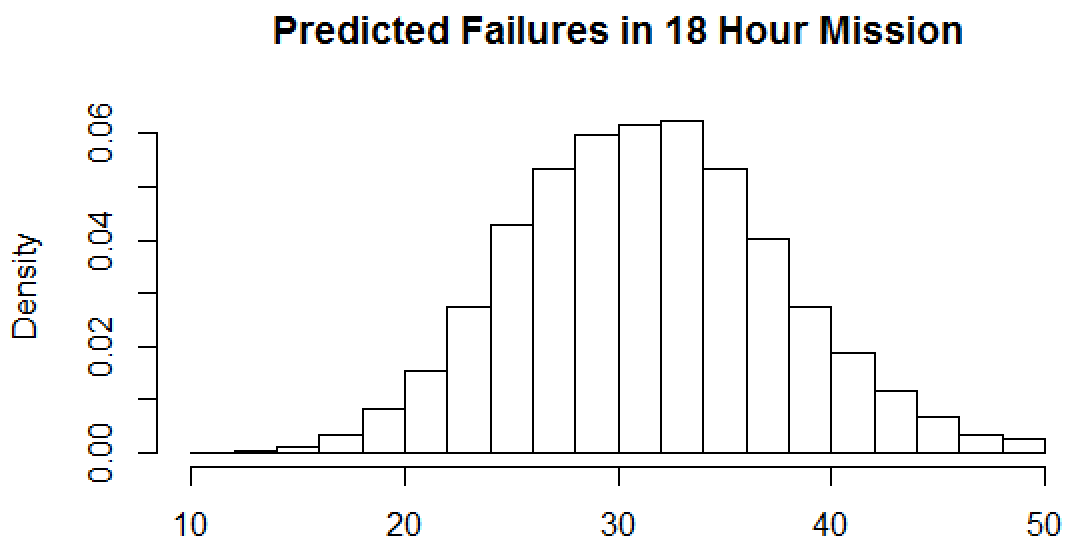
Evidence not all missions have same failure rate

Evidence not all activities have same failure rate (here, from Mission 1)



DIC = 119.19

Model 1 Mission Reliability



With this model, there is no way to account for variation in mission: a mission is simply 18 hours of operation.

Sequence of Models

Model 2: Accounting for Mission Differences (one failure rate per mission, hierarchical prior)
Model 3: Accounting for Activity Differences (one failure rate per activity)
Model 4: Accounting for Mission and Activity Differences (one failure rate per mission-activity combination)

- The models consistently provide evidence that different missions have different failure rates and that different activities have different failure rates.
- When we use a criterion like DIC to check model fit, the penalty for the increasing number of parameters outweighs the improvement in fit for Model 4.

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Looking Forward (1)

- **How do we use data from developmental testing, limited user testing, and the test-fix-test paradigm?**
  - Developmental testing is not necessarily “operationally realistic.” It may, however, give us estimates of failure rates for specific activities.
  - It then becomes a modeling question about how we understand the changes in failure rates due to changes in operational realism and fixes to the system.

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Experimental Design Approach

The simulated data used an "experimental design" approach to generating data

- Five missions followed a factorial design with center point layout
- No replication
- No controlling for order effects
  - It probably isn't reasonable to assume that the later missions are not impacted by the earlier missions, especially in the case of crew-induced failure modes. Does that suggest we should start easy and progress to hard or randomly select, etc.?
- Limited data (5 missions with limited failures) provides low statistical power to test for mission effects

Experimental Design Approach

Why experimental design then?

- Ensures coverage of operational mission usage
- If failure rates change dramatically by mission, then we have a chance to detect this change
  - It is not unreasonable to assume that "operational tempo" might impact failure rates

Looking Forward (2)

- **What's a smart way to design the sequence of tests to let us understand mission reliability?**
  - PIM is a relatively simple mixing of three primary activities to make a mission
  - Ships may consist of dozens of tasks using dozens of system functions to complete very different looking missions
  - Can we expand this analysis to address complex systems more holistically than simply converting to hours?

- **Can we adapt assurance testing ideas to plan the OT?**
  - Is there a better breakdown for covering missions than a simple experimental design approach?