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Bayesian Component Reliability Estimation: an F-35 Case Study

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Executive Summary

A challenging aspect of a system reliability assessment is integrating multiple sources of information, such as component, subsystem, and full-system data, along with previous test data or subject matter expert (SME) opinion. A powerful feature of Bayesian analyses is the ability to combine these multiple sources of data and variability in an informed way to perform statistical inference. This feature is particularly valuable in assessing system reliability where testing is limited and only a small number of failures (or none at all) are observed.

The F-35 is DoD's largest program; approximately one-third of the operations and sustainment cost is attributed to the cost of spare parts and the removal, replacement, and repair of components. The failure rate of those components is the driving parameter for a significant portion of the sustainment cost, and yet for many of these components, available estimates of the failure rate are poor. For many programs, the contractor produces estimates of component failure rates based on engineering analysis and legacy systems with similar parts. While these estimates are useful, the actual removal rates provide a more accurate estimate of the removal and replacement rates the program will experience in future years.

In this document, we show how we applied a Bayesian analysis to combine the engineering reliability estimates with the actual failure data to estimate component reliability. Our analysis technique also allows for us to overcome the problems of cases where few or no failures have been observed. We are able to show that combining the engineering knowledge of reliability with the observed operational reliability results in both a more informed estimate of each individual component's reliaiblity and a more informed estimate of overall F-35 maintenance costs.

The technique presented is broadly applicable to any program where multiple sources of reliability information need to be combined for the best estimation of component failure rates, and ultimately of sustainment costs.

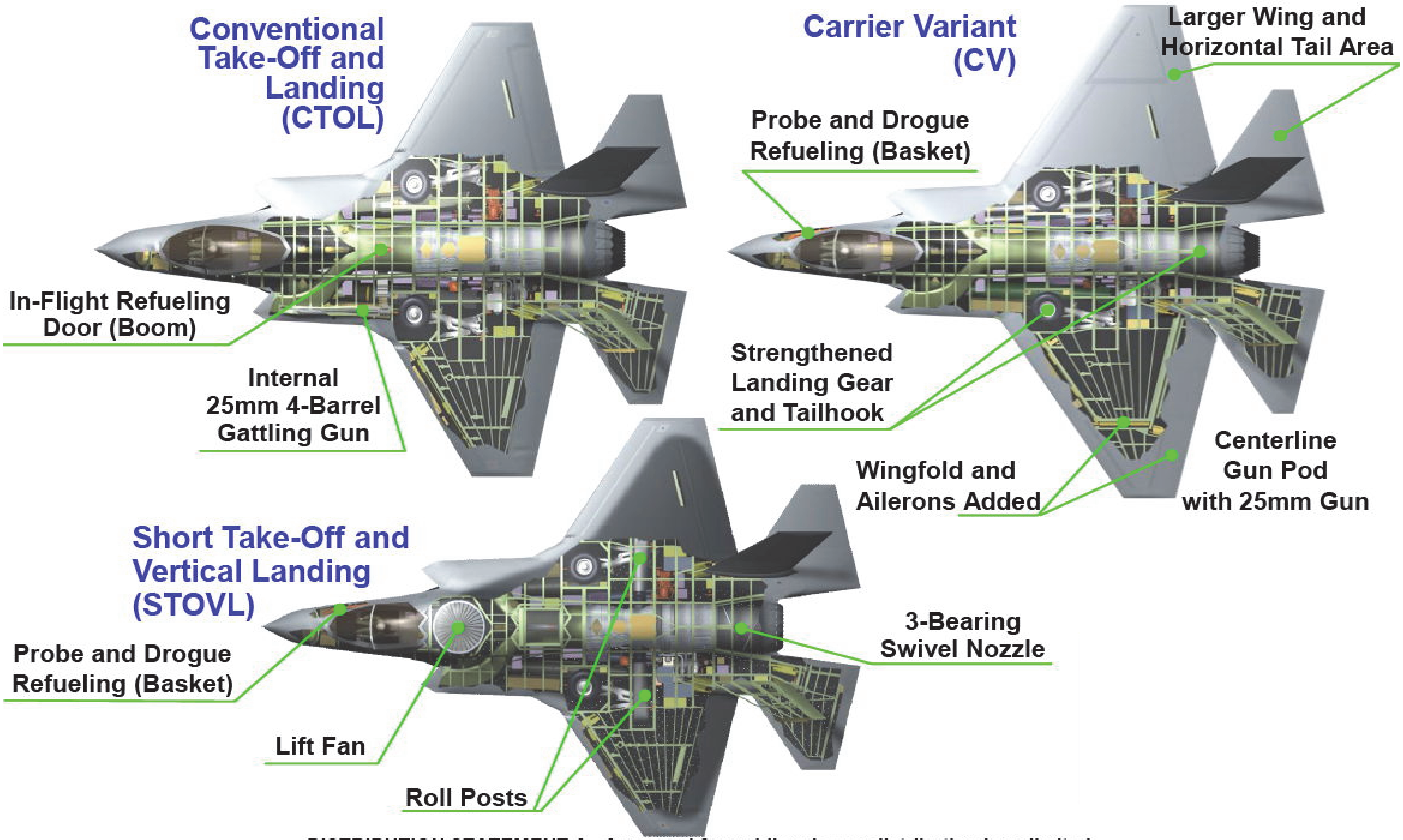
Bayesian Component Reliability Estimation: an F-35 Case Study

Bram Lillard

Rebecca Medlin

April 2019

F-35 is a complex aircraft…



Estimating Component Reliability is essential for Operations and Sustainment

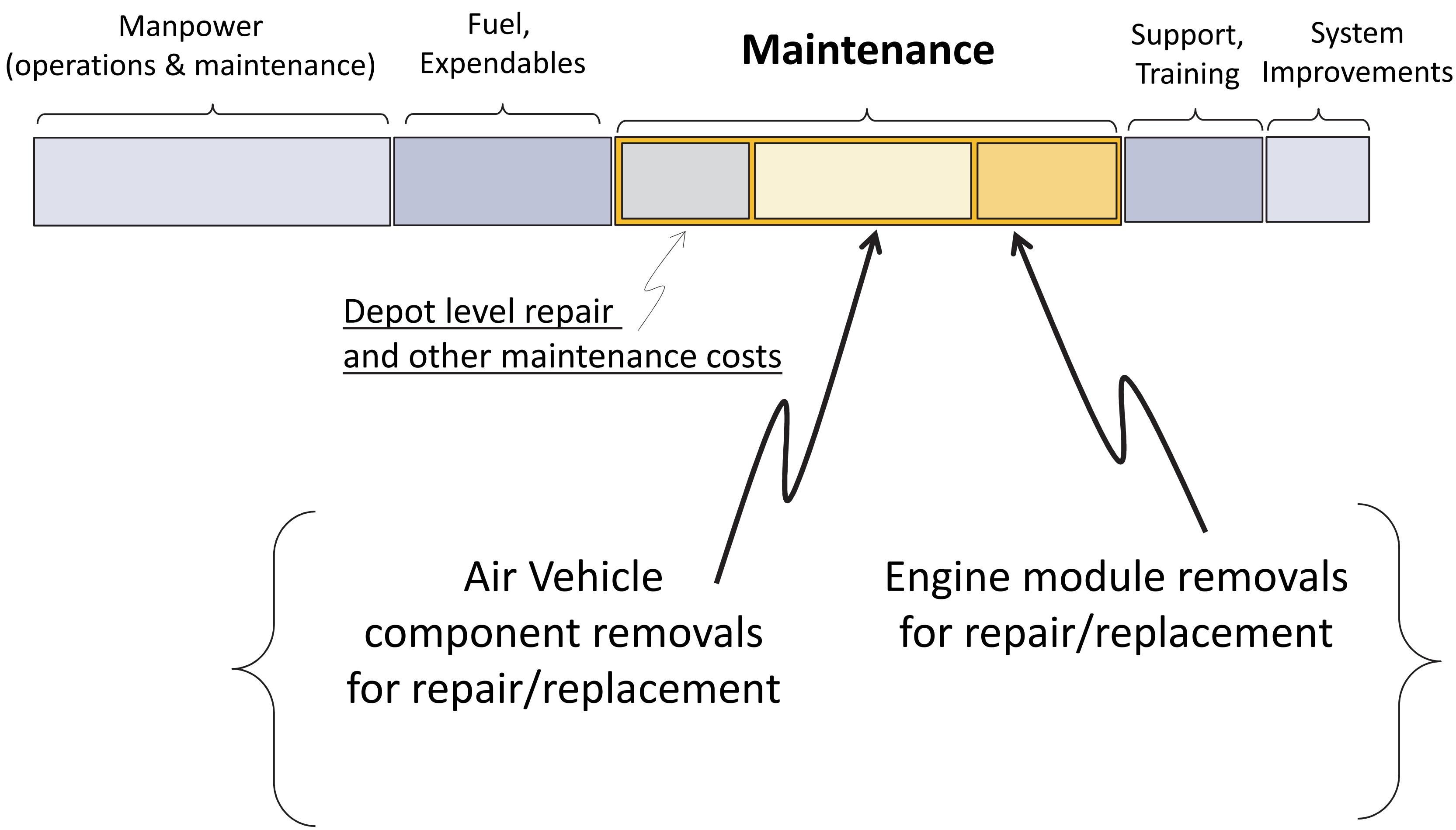
Over 2,000 parts

Air Vehicle Systems	# components within category
PWR & THERMAL MGMTSYS (PTMS)	88
270VDC GENERATION AND DIST	28
CONTROL PANELS	26
SENSORS, WPNS BAY, ENG BAY	46
CONTROL SURFACES	49
FUEL SYSTEM	141
ICE DETECTION	5
LANDING GEAR	261
LIGHTING	31
IMU & IEU	16
OXYGEN GEN	7
HELMET AND DATA PROCESSORS	52
PHM AIR VEHICLE	7
VEHICLE SYS PROCESSING (VSP)	16
CNI SYSTEM	70
STANDARD PRACTICES, STRUCTURES	38
DOORS & COVERS	330
FRAME, BULKHEADS	113
STABILIZERS, RUDDER	40
CANOPY	27
STRUCTURE, FARINGS, FLAPS	92
PROPULSION AIRCRAFT INTERFACE	9
THROTTLE	6
DOOR ACTUATORS (STOVL ONLY)	49
RADAR SYSTEM	149
EJECTION SEAT, SYSTEM	34
ELECTRONIC WARFARE	81

<u>Reliability estimates drive</u>:

- Spares purchases
- Program budgeting
- Cost estimation
- Readiness

What comprises F-35 Costs per Flying Hour?



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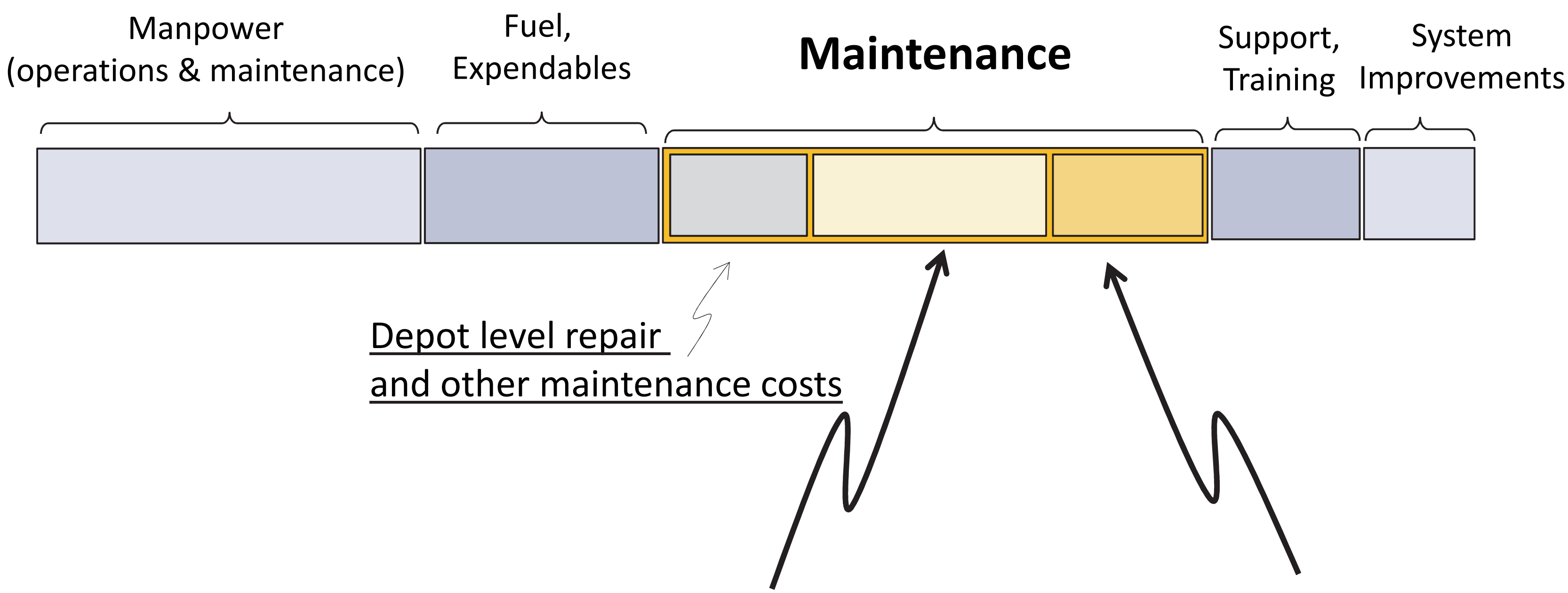
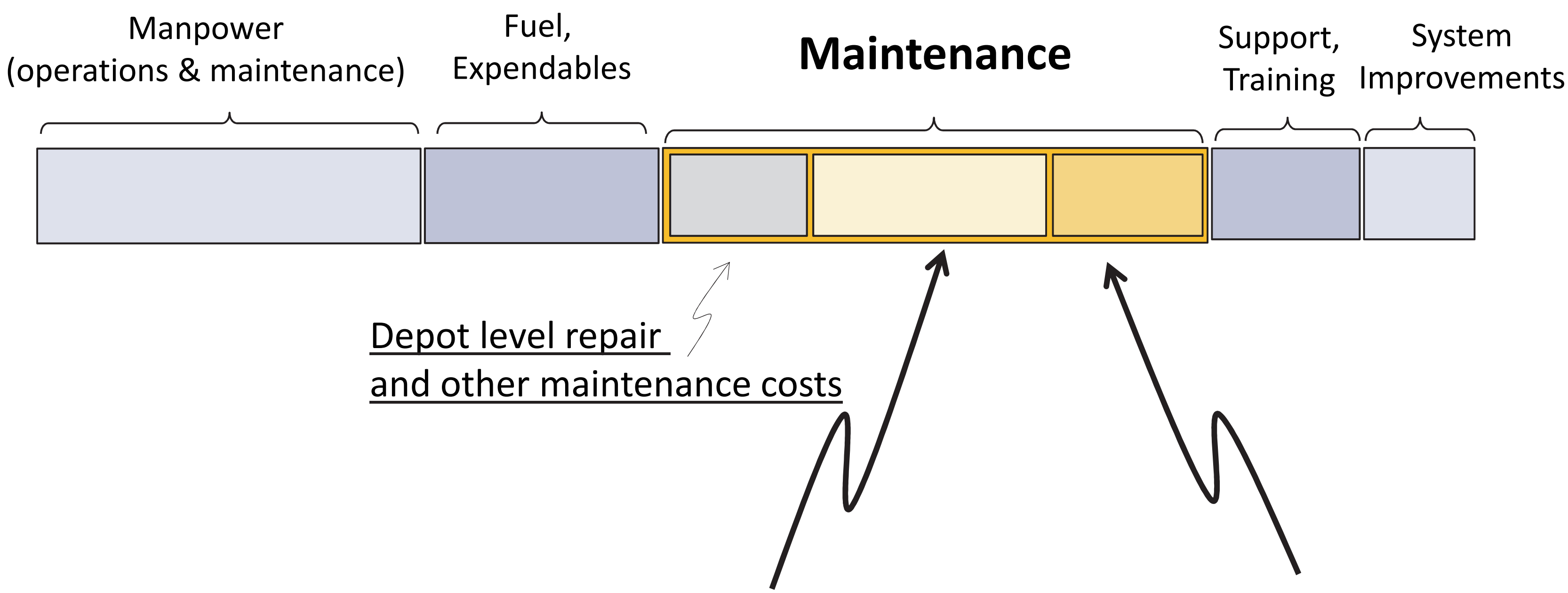


$$CPFH_{Total} = \sum_{i=1}^{n} \frac{[Replacement\ or\ Repair\ Cost]_i \times (num\ failures)_i}{Total\ Flight\ Hours}$$

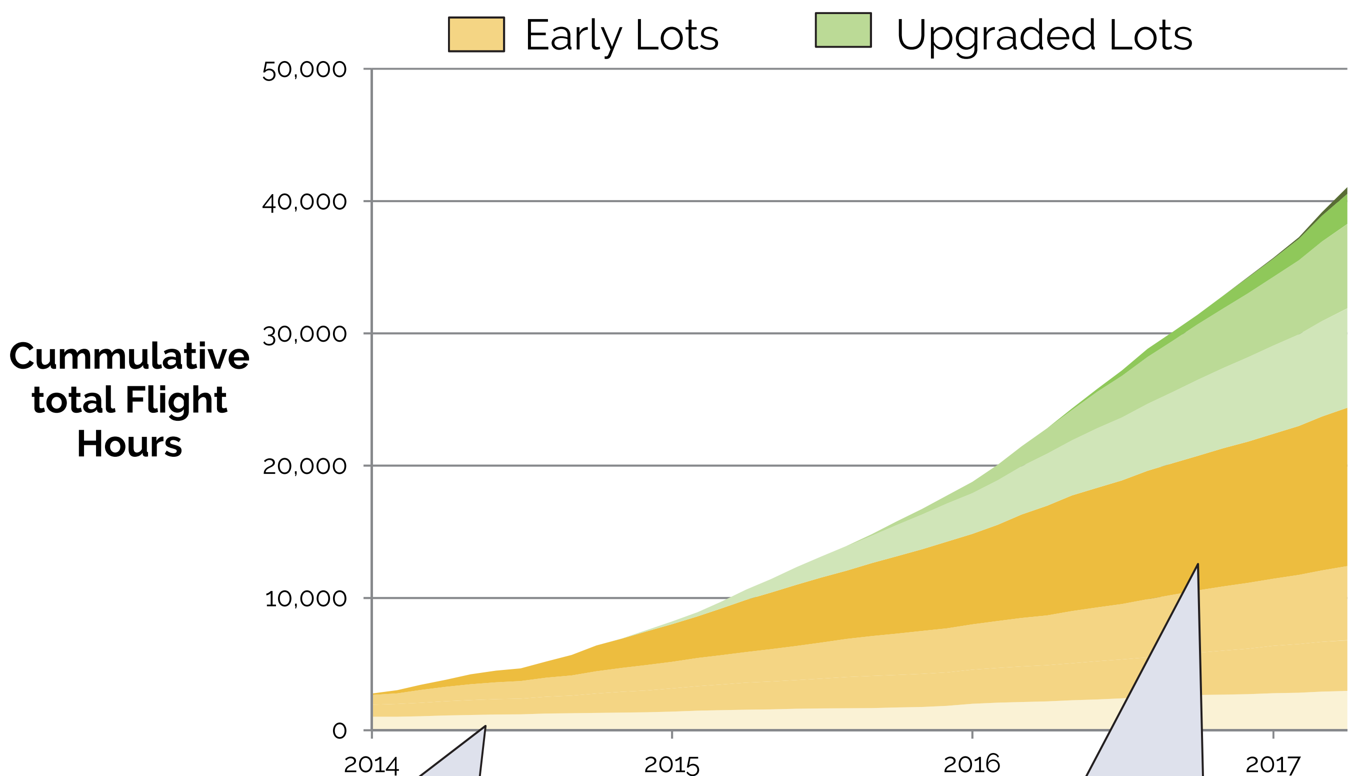
What comprises F-35 Costs per Flying Hour?



$$CPFH_{Total} = \sum_{i=1}^{n} \frac{[Replacement\ or\ Repair\ Cost]_i}{\mathrm{MFHBR}_i}$$

Accurate component Reliability estimates
are essential for cost estimation

Data is often scarce for reliability estimation



Early in a Program we only have ***Engineering Estimates*** for component reliability (also when a new variant/configuration begins flying)

Later, sufficient failures have occurred, flying hours accumulated, to begin estimating reliability for each component

Component Reliability Estimates – Many methods

Three Cases

Lots of failures (N>20)

$$MFHBR_i = \frac{Total\ Flight\ Hours}{N_i}$$

(assume failure times follow an Exponential Distribution)

Few failures (1 < N < 20)

Do we use:

- FH/N (ignore uncertainty)?
- Report a weighted average?
  - E.g., 0.3*(FH/N) + 0.7*Eng. Est.

No Failures to date (N=0)

$$MFHBR_i = MFHBR_i^{Engineer\ Est.}$$

What if FH >> $MFHBR_i^{Engineer\ Est}$?

Do we use the:

- lower CI bound?
- set equal to FH?
- engineering est.?

Alternatively we can use a Bayesian approach
(sliding scale weighted average)

N = number of failures; FH = Flight Hours

Bayesian statistics combine "prior" knowledge with observed data to produce an estimate

Example for Component X:

- Engineering Estimate MFHBR = 990 hours
- Flight Hours flown to date: 40,000 hours
- Observed 2 Failures…. traditional methods estimate:
- MFHBR = 40,000 / 2 = 20,000 hours

What's the best number to use for MFHBR?

990 or 20,000?

Average the two? (~10,500?)

Weigh one more than the other? Which one?

One math slide for the presentation…

Bayesian approach to estimating Relatability

$$\underbrace{\pi(\lambda|\boldsymbol{x})}_{\text{Posterior Distribution}} \propto \underbrace{L(\boldsymbol{x}|\lambda)}_{\text{Likelihood Distribution}} \underbrace{\pi(\lambda)}_{\text{Prior Distribution}}$$

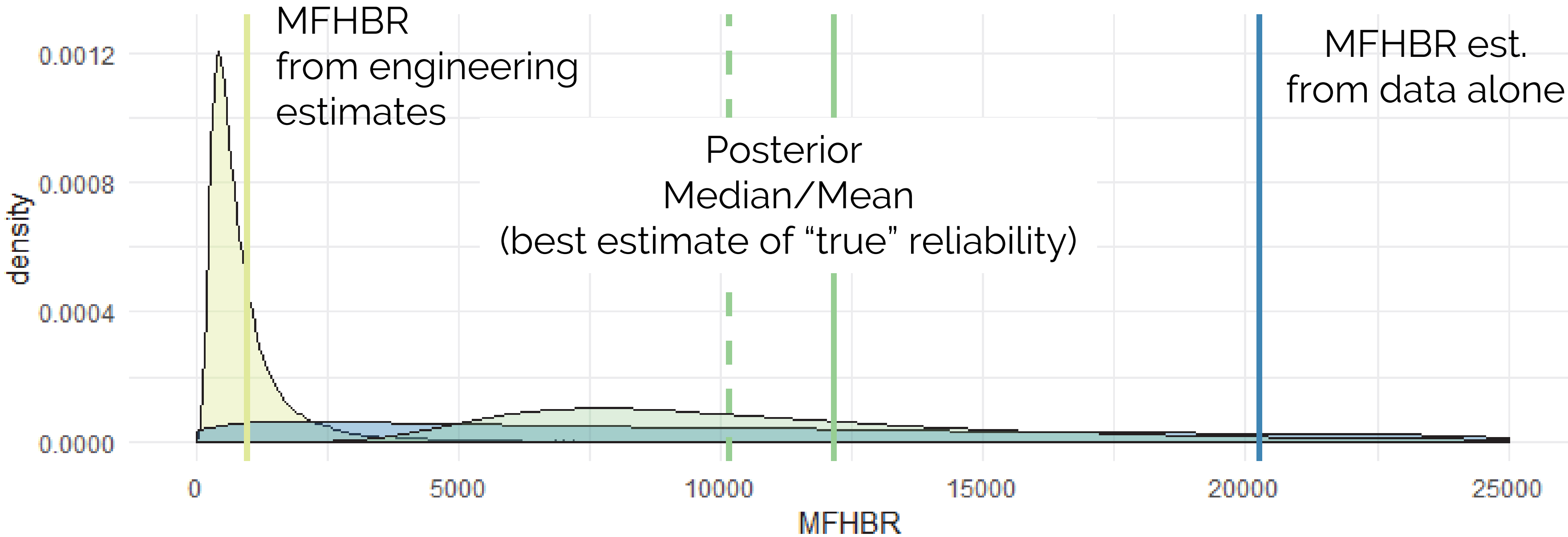
- **Likelihood Distribution:** Exponential (λ)
  - $MFHBR = \frac{1}{\lambda} = \frac{Total\ Flight\ Hours}{n}$
- **Prior Distribution:** Gamma (α, β)
  - We can use the engineering estimates to solve for α and β.
  - Inv. Gamma mean = $MFHBR_{Engineer\ Est}$
  - Inv. Gamma std. = $MFHBR_{Engineer\ Est}\ x\ p$
- **Posterior Distribution:** Gamma ($\alpha`, \beta`$)
  - $\alpha` = N + \alpha$
  - $\beta` = Total\ Flight\ hours + \beta$

p = the “confidence” we place in the prior information. We used a p = 1.5.

Bayesian statistics combine "prior" knowledge with observed data to produce an estimate

Example for Component X:

- Engineering Estimate MFHBR = 990 hours (yellow "prior" below)
- Flight Hours flown to date: 40,000 hours
- Observed 2 Failures…. traditional methods estimate:
- MFHBR = 40,000 / 2 = 20,000 hours (blue "likelihood" below)



Bayesian statistics combine "prior" knowledge with observed data to produce an estimate

Example for Component X:

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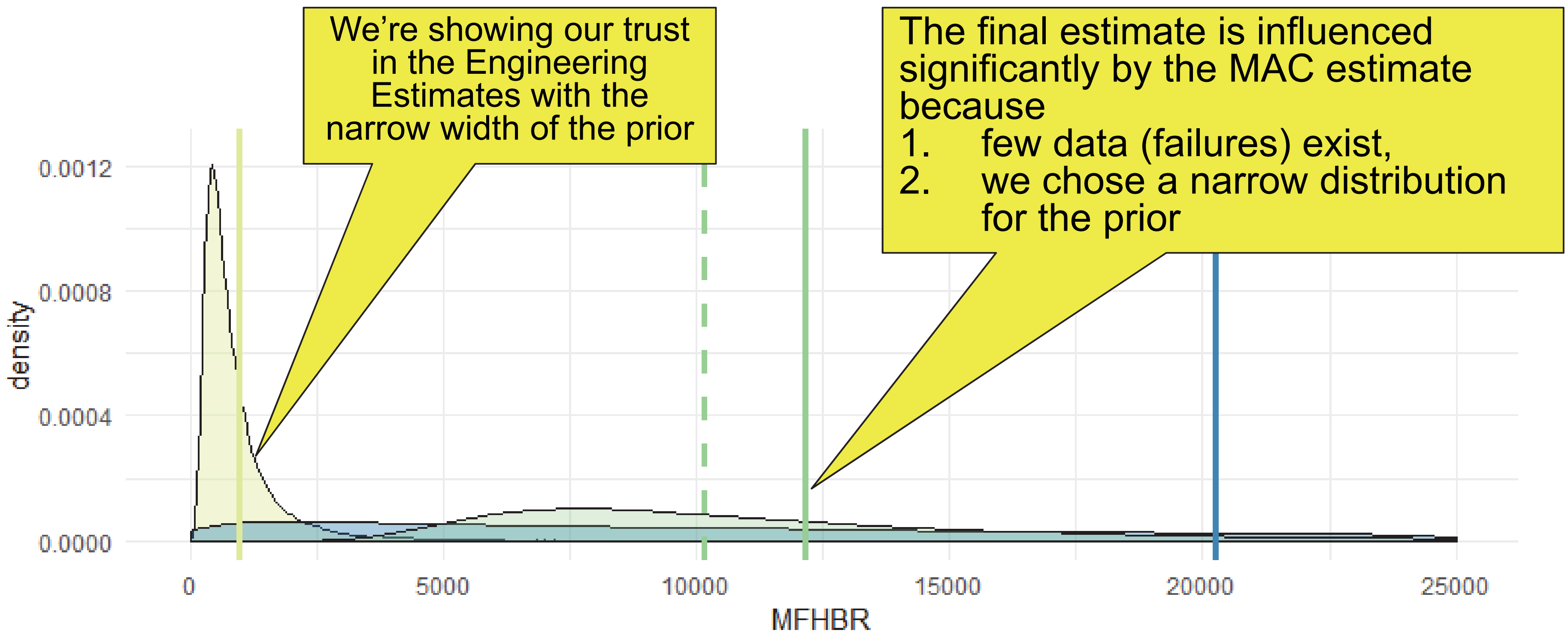
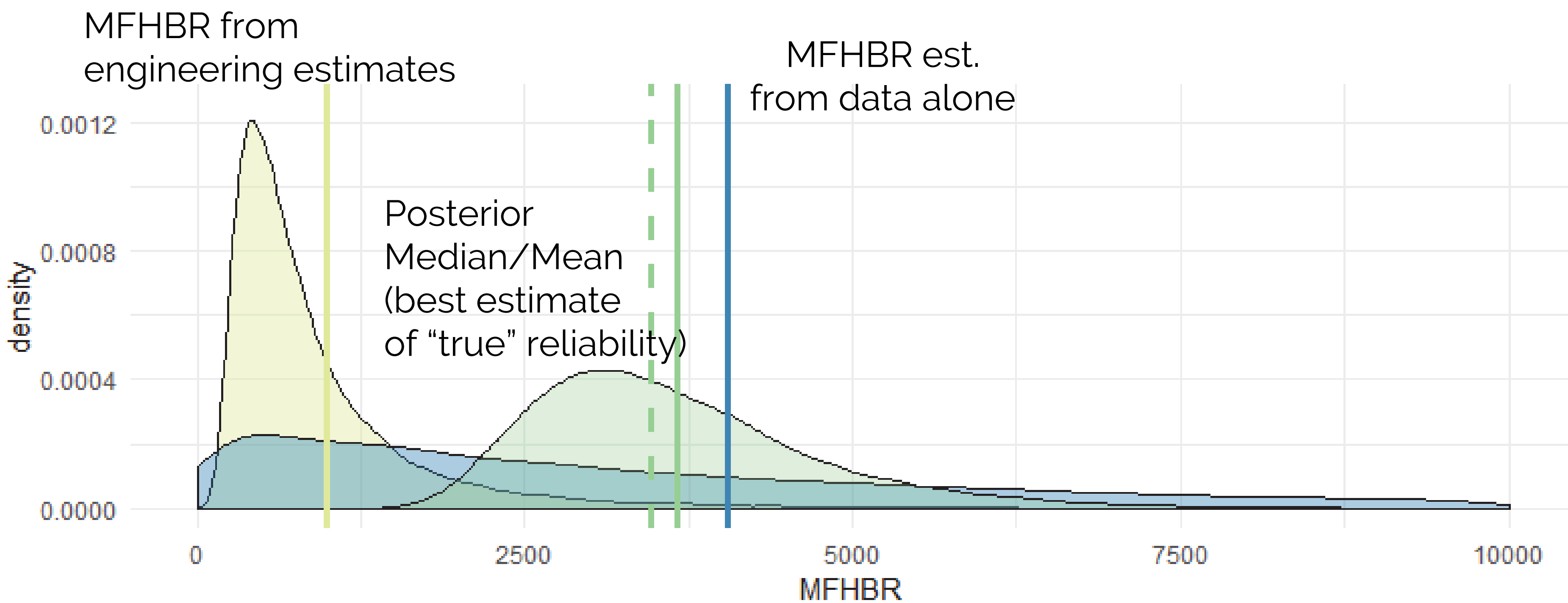
- MFHBR = 40,000 / 2 = 20,000 hours (blue "likelihood" below)



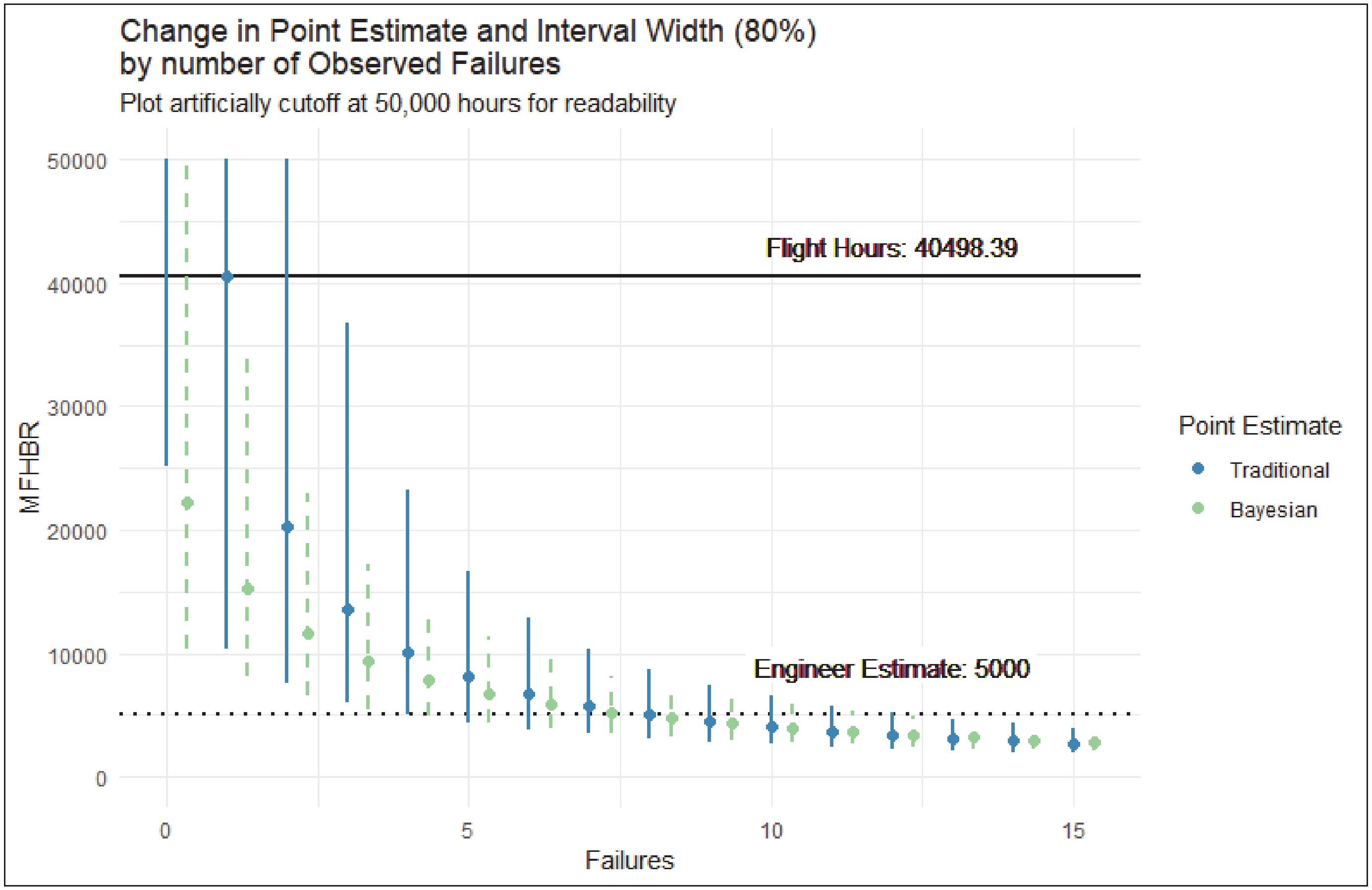
With more failure data available, the final estimate is less influenced by the MAC value

<u>Example for Component Y:</u>

- Engineering estimates: MFHBR = 990 hours (yellow prior below)
- Flight Hours flown to date: 40,000
- Observed 10 Failures, so, traditional methods estimate:
- MFHBR = 40,000 / 10 = 4,000 hours (blue "likelihood" below)



A robust methodology for all cases



- Bayesian method appropriately moves MFHBR estimate towards the traditional result as the available data increases
- The approach also automatically handles cases where N=0 (something not satisfactorily handled with traditional approaches)

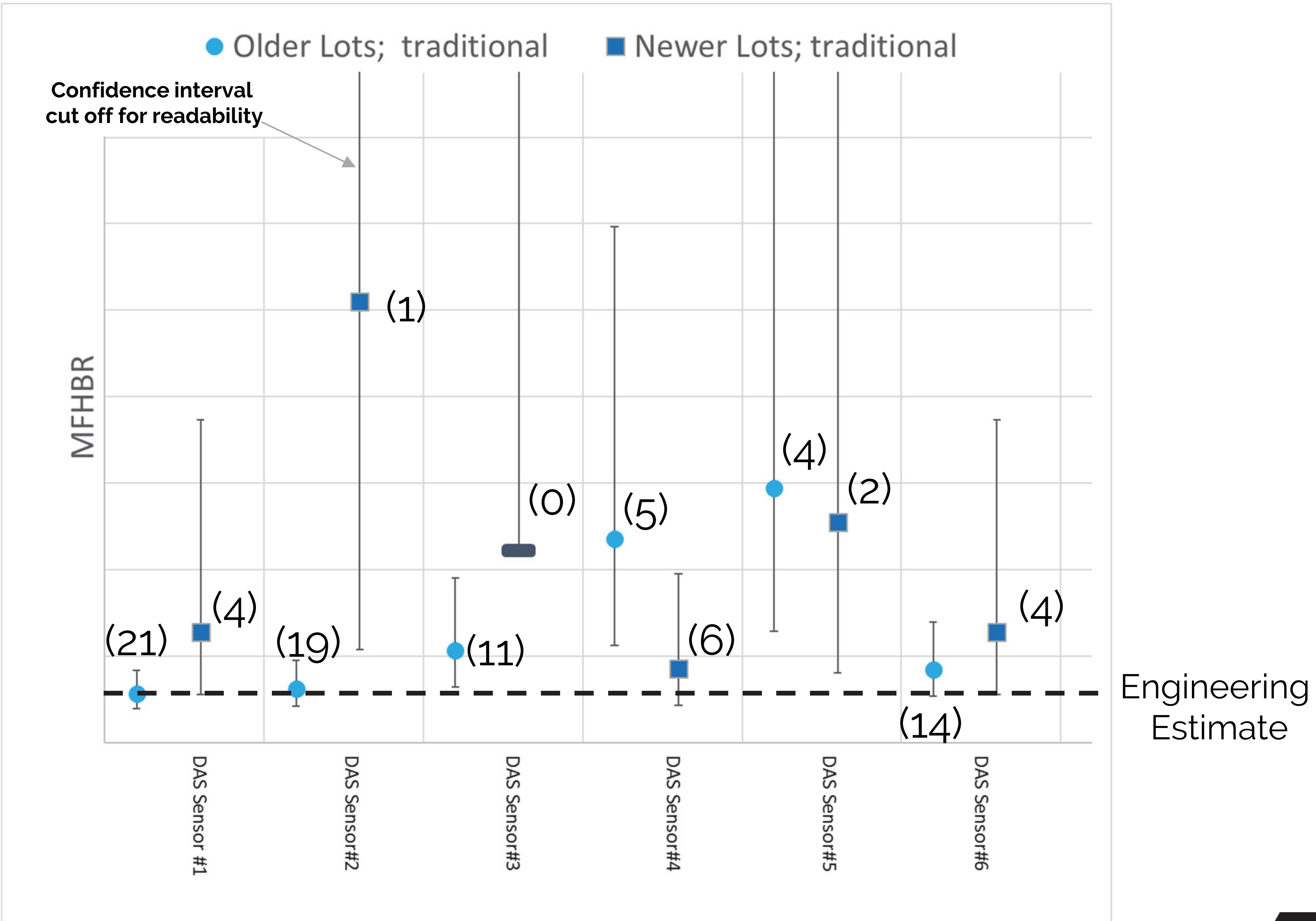
A frequent debate:
How do we estimate MFHBR for a new configuration?

Example for Component Z:

	Older Lots	New Lots (anticipated improvement)
Engineering Estimate	900	900
Flight hours	20,000	10,000
Failures observed	5	0
MFHBR	4,000	3,338? (95% Lower bound) 4,000? (LRIP 2-5 estimate) 900? (Eng. Est.)

- Bayesian method provides an ideal (and defensible) calculation method for this case
- MFHBR for Older Lots serves as the ***new prior estimate*** for the New Lots calculation
  - Appropriately using the available data as a starting point, but allowing the available New data to dictate how much the final estimate is moved
- Bayesian results for New Lots : MFHBR = 7,576

Distributed Aperture System Sensors' reliability show the benefit of the Bayesian approach



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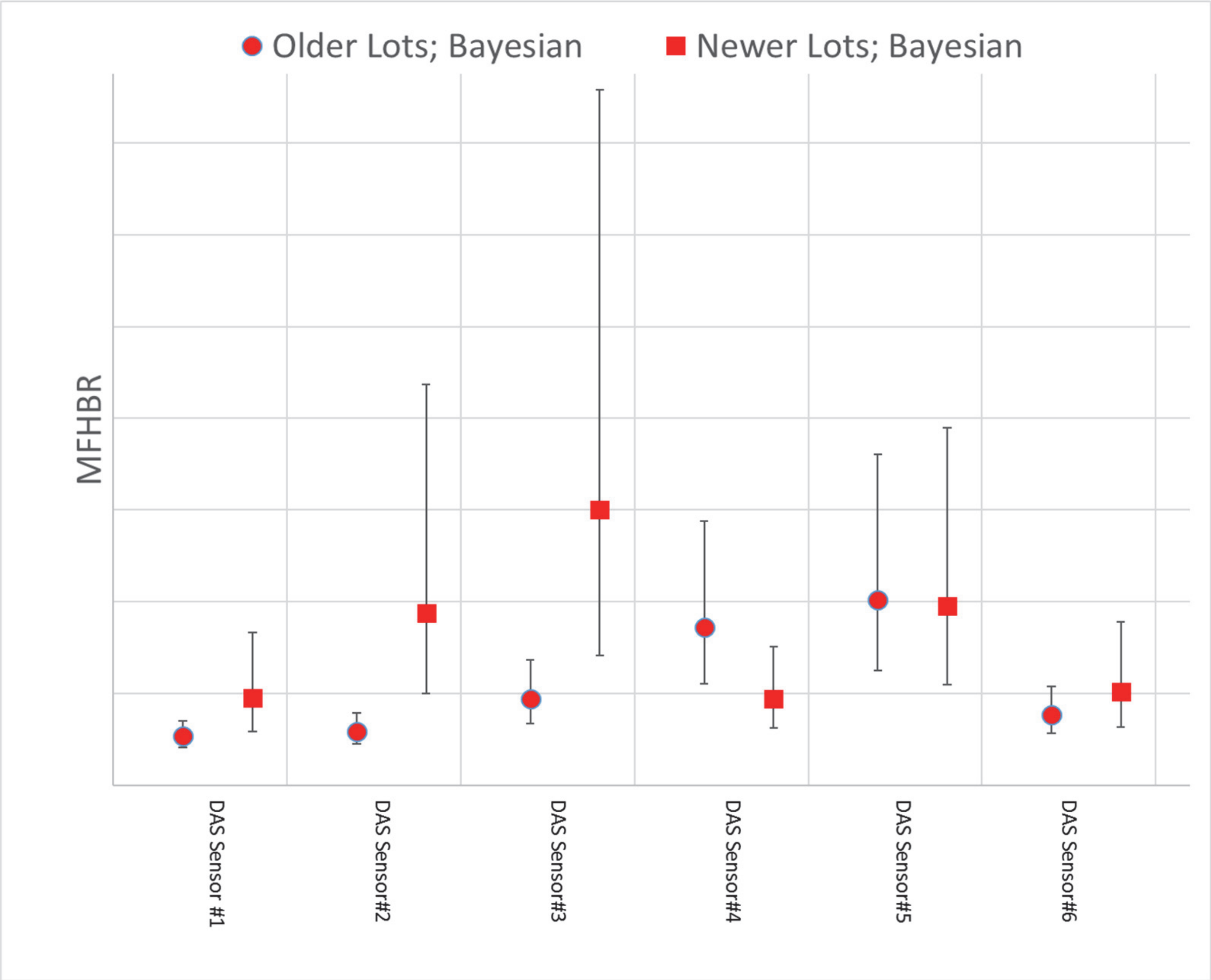

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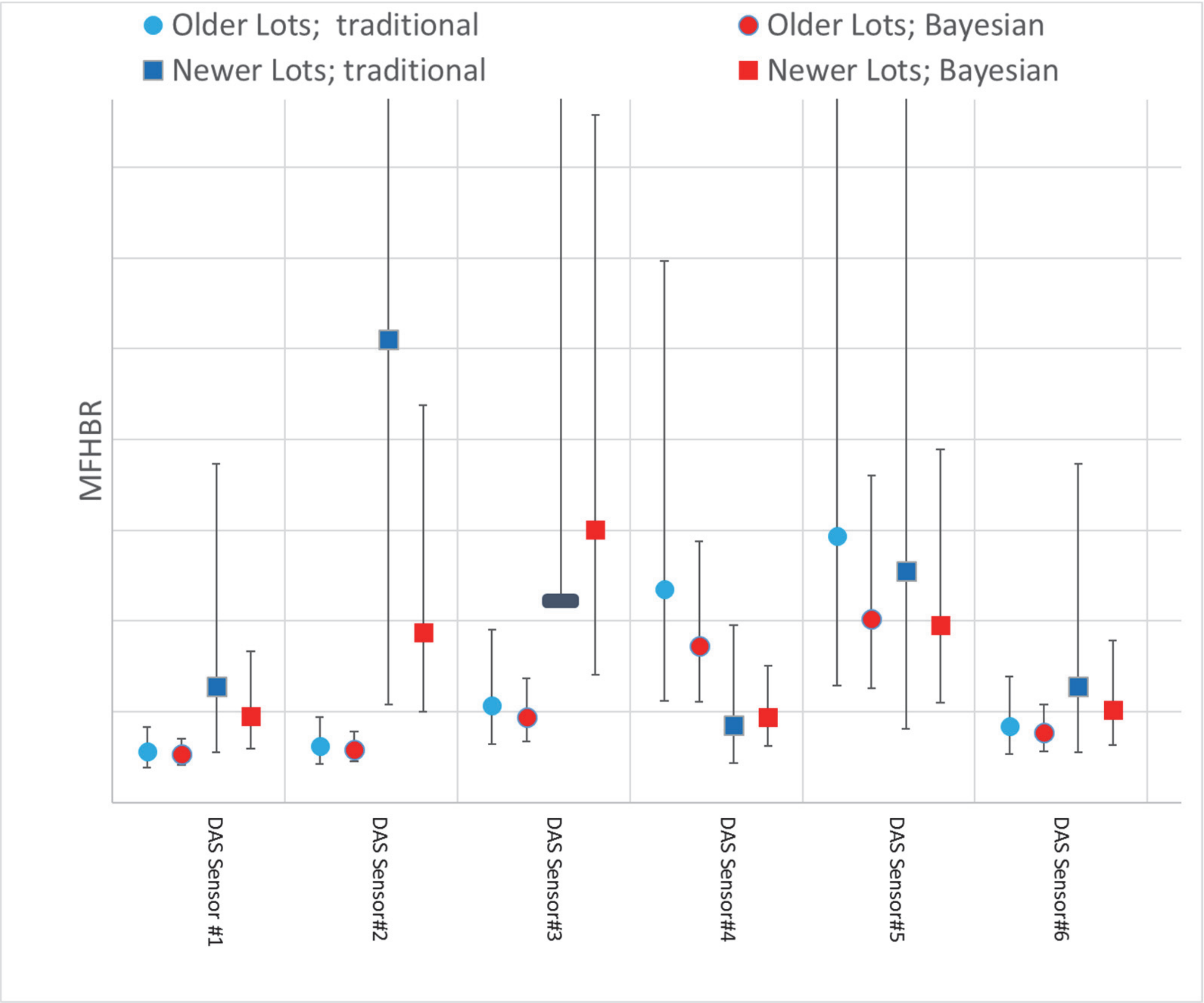

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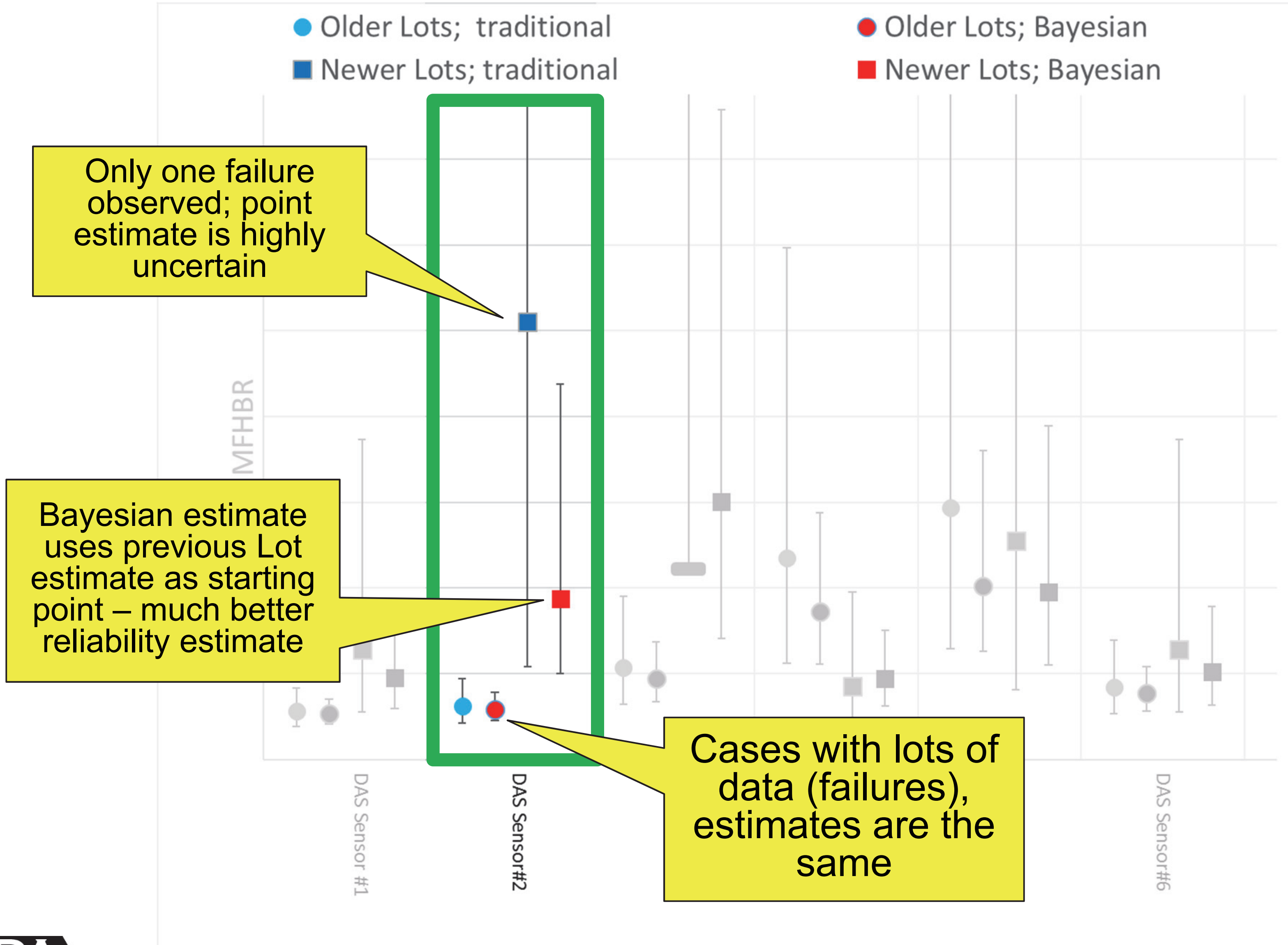

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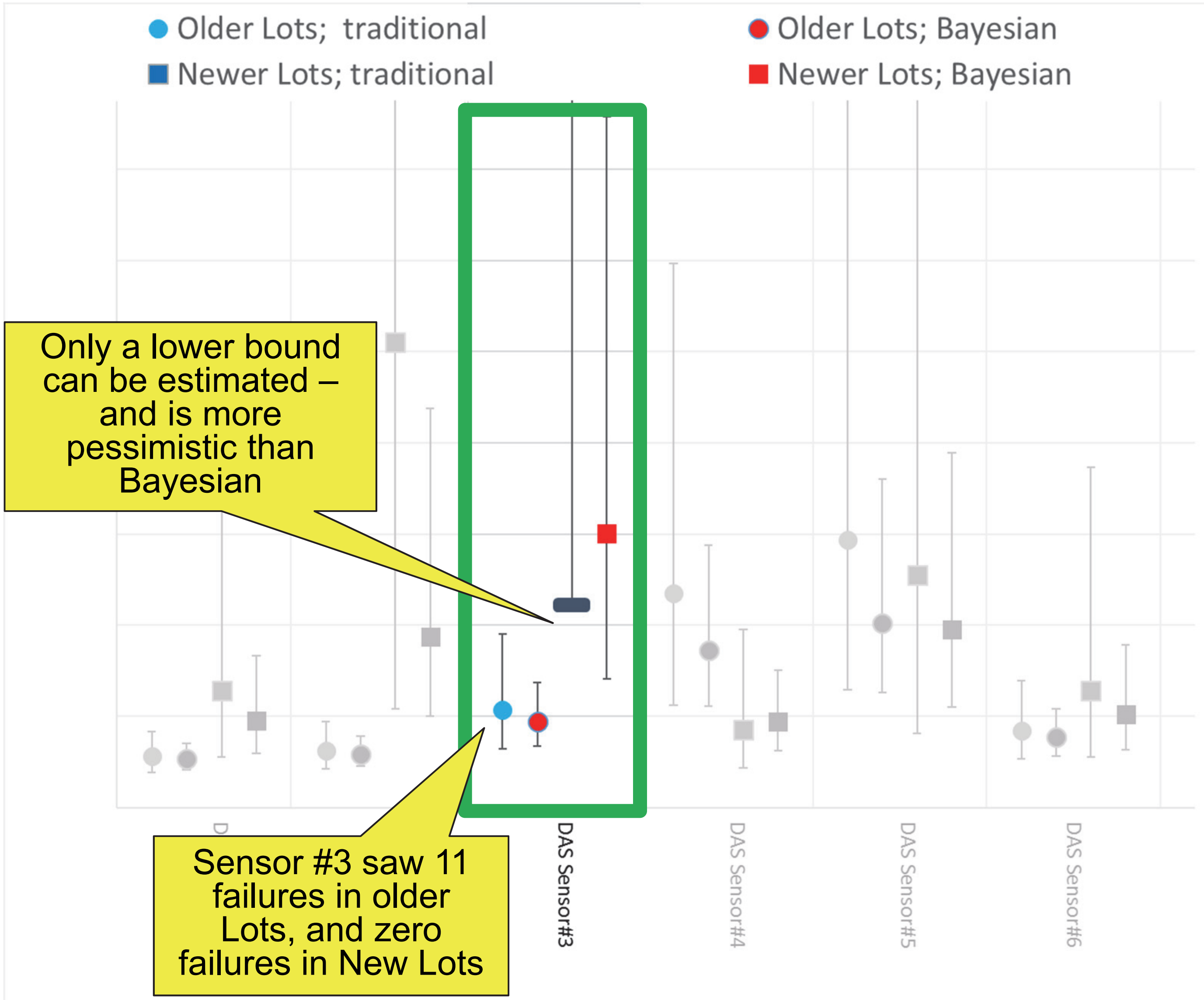

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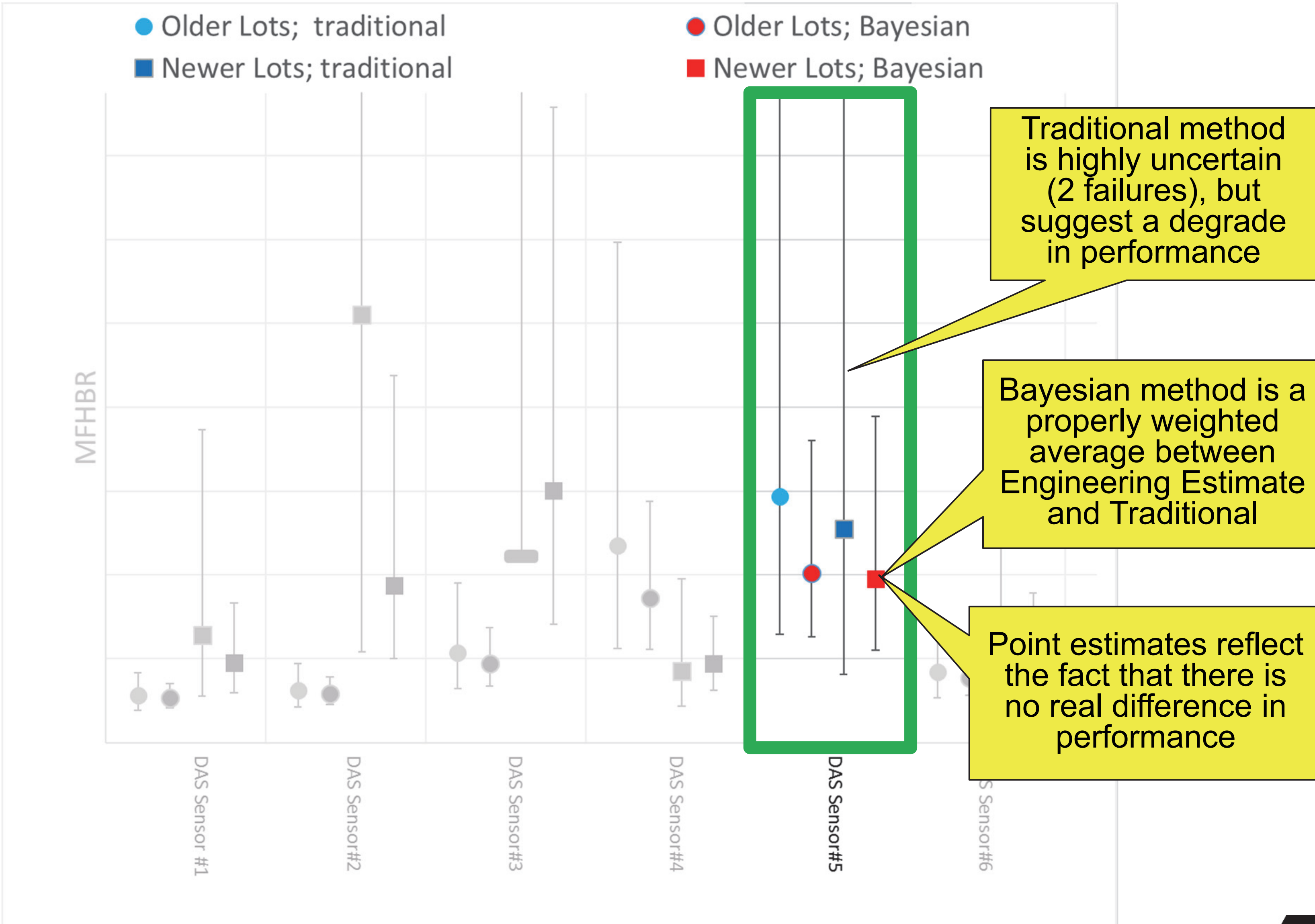

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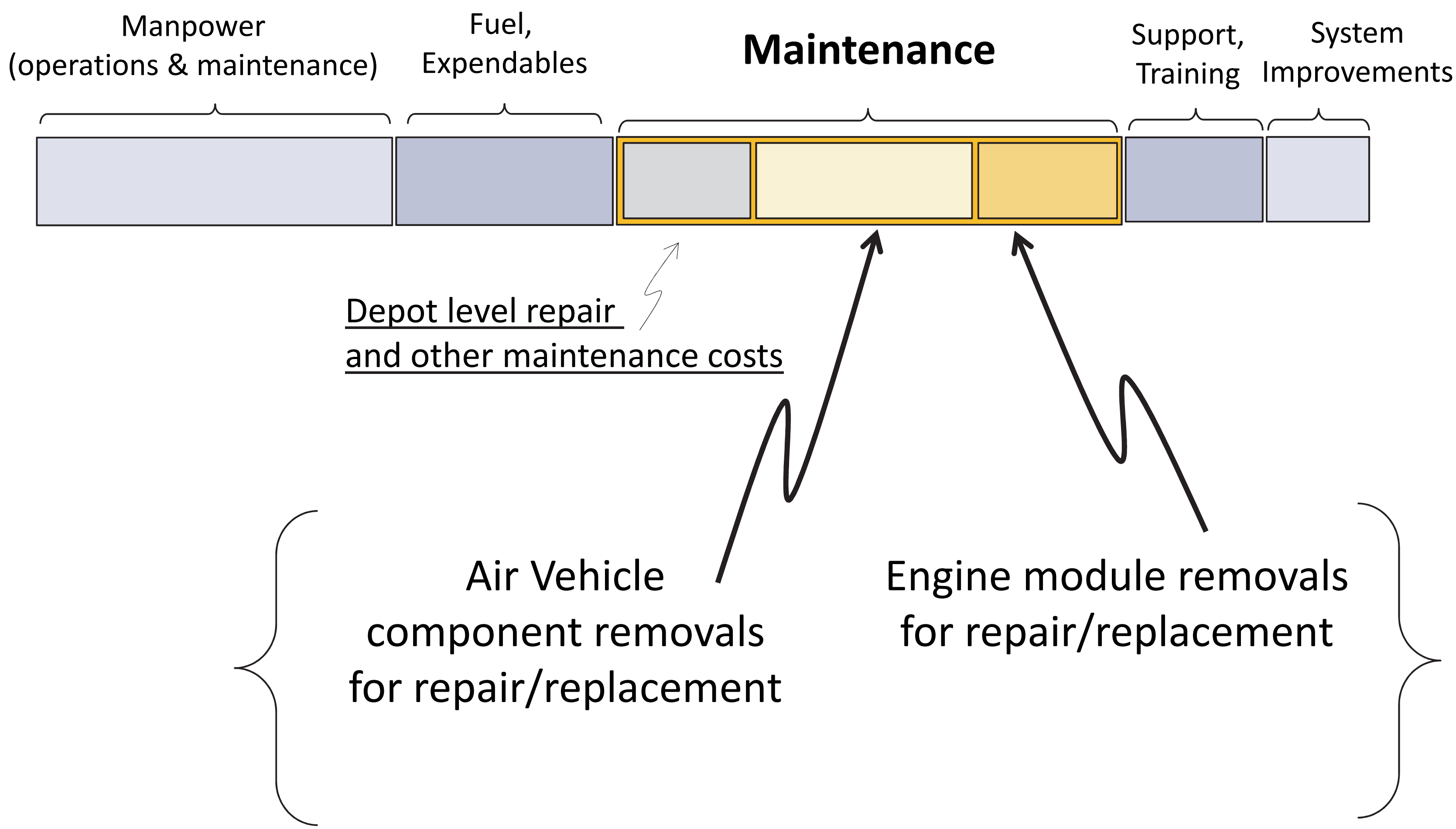
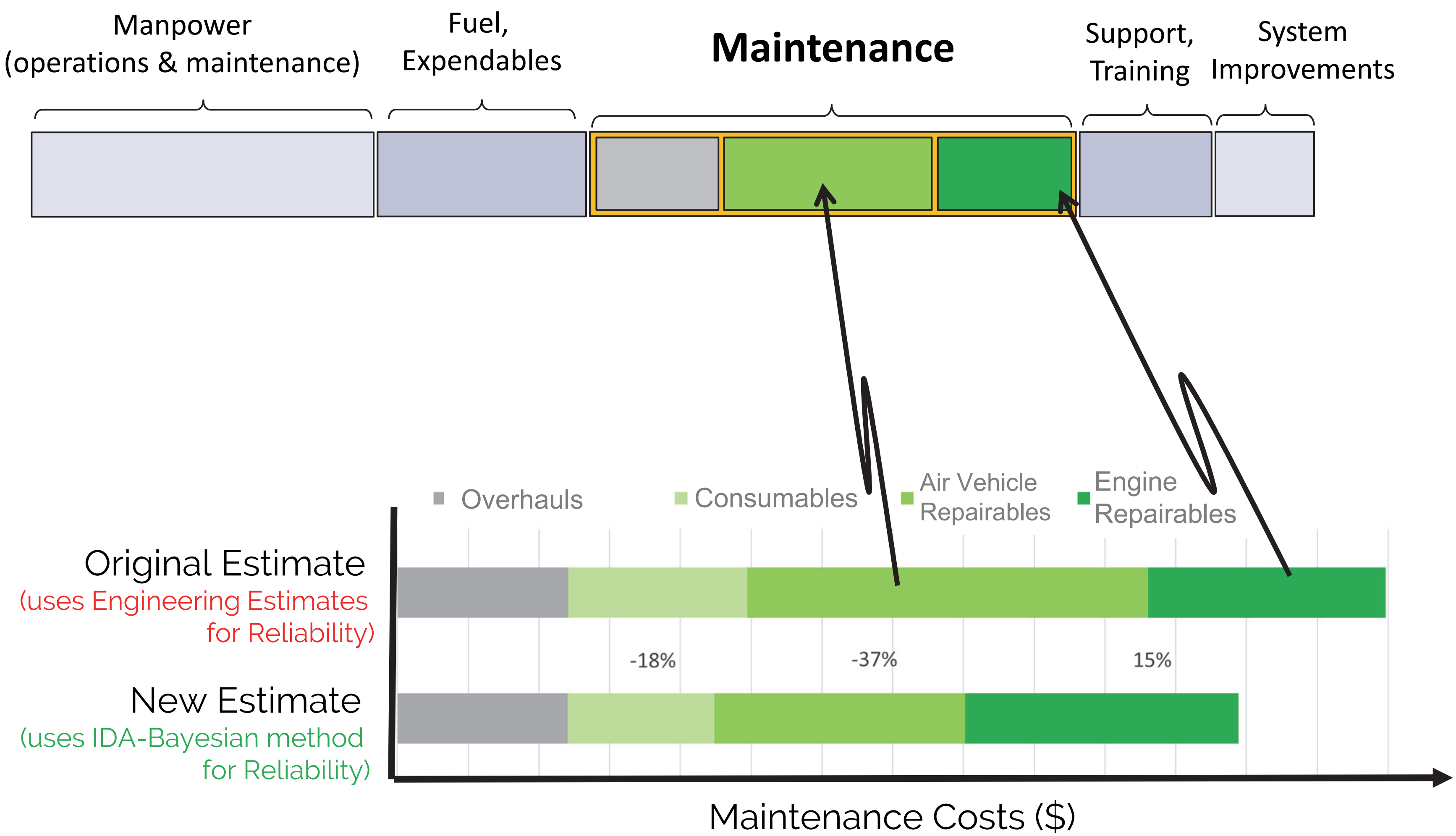


Bayesian Reliability results in a more informed estimate of maintenance costs



Conclusion

Bayesian methods provide a means to combine available knowledge of reliability with operational data to estimate component reliability, resulting in a more informed estimate of F-35 maintenance costs.

- Updated from early engineering estimates
- Updated from previous system/variant data
- Handles cases with few data (even no failures!)

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Project Leader: Vincent Lillard (OED)

14. ABSTRACT

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