Bayesian Component Reliability Estimation: an F-35 Case Study

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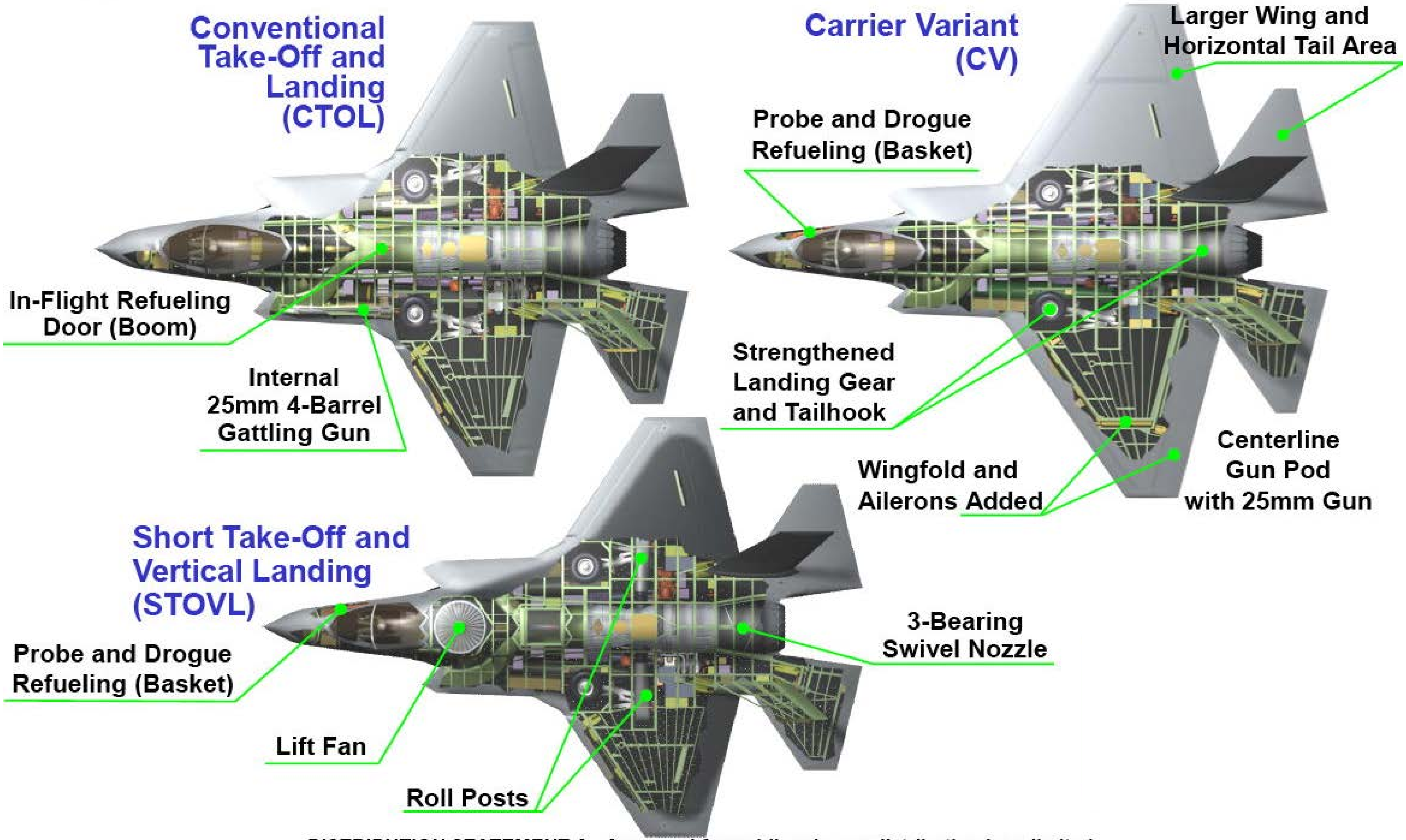
F-35 is a complex aircraft…



Estimating Component Reliability is essential for Operations and Sustainment

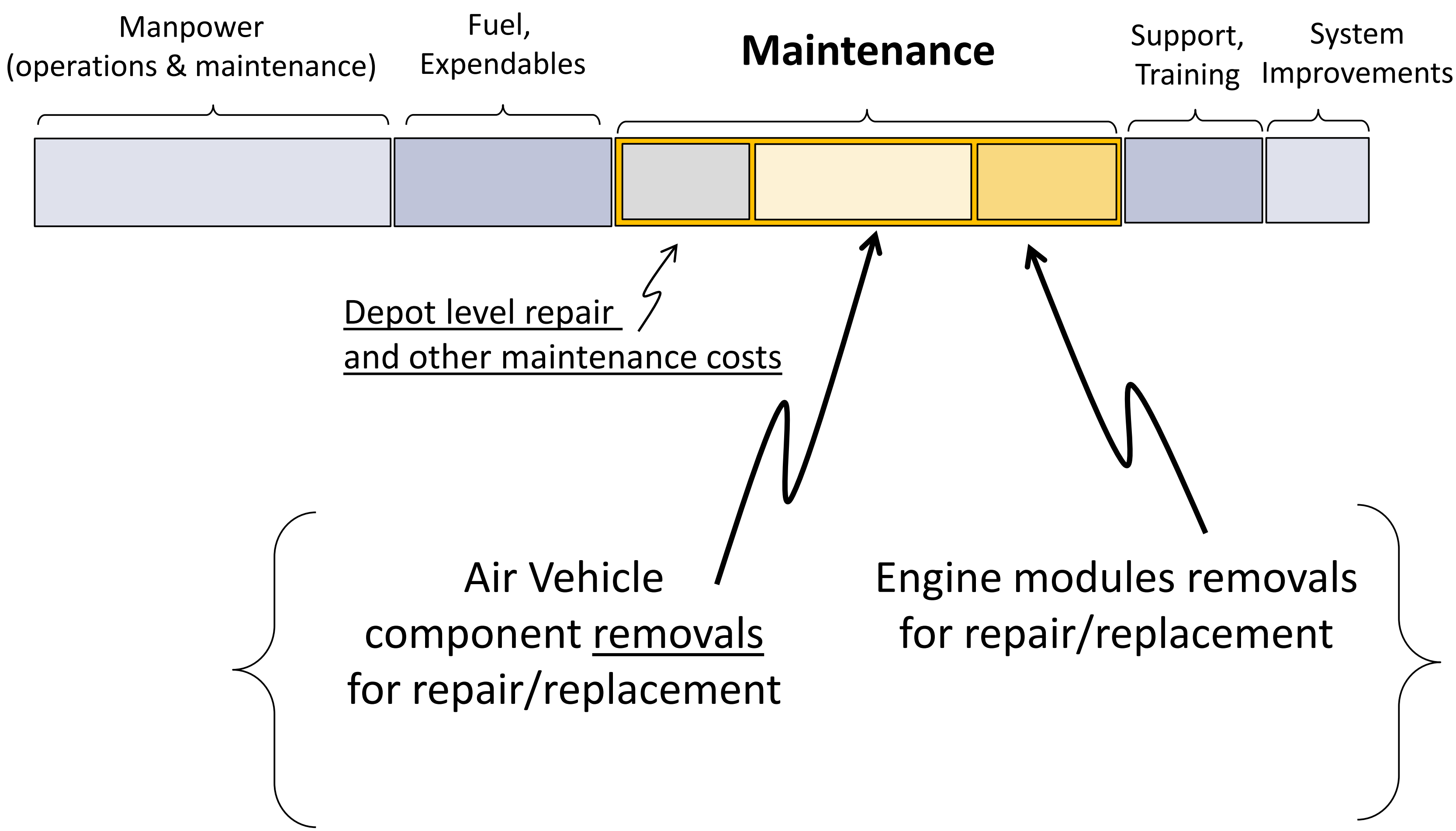
Over 2,000 parts

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

Reliability estimates drive :

- Spares purchases
- Program budgeting
- Cost estimation
- Readiness

What comprises F-35 Costs per Flying Hour?



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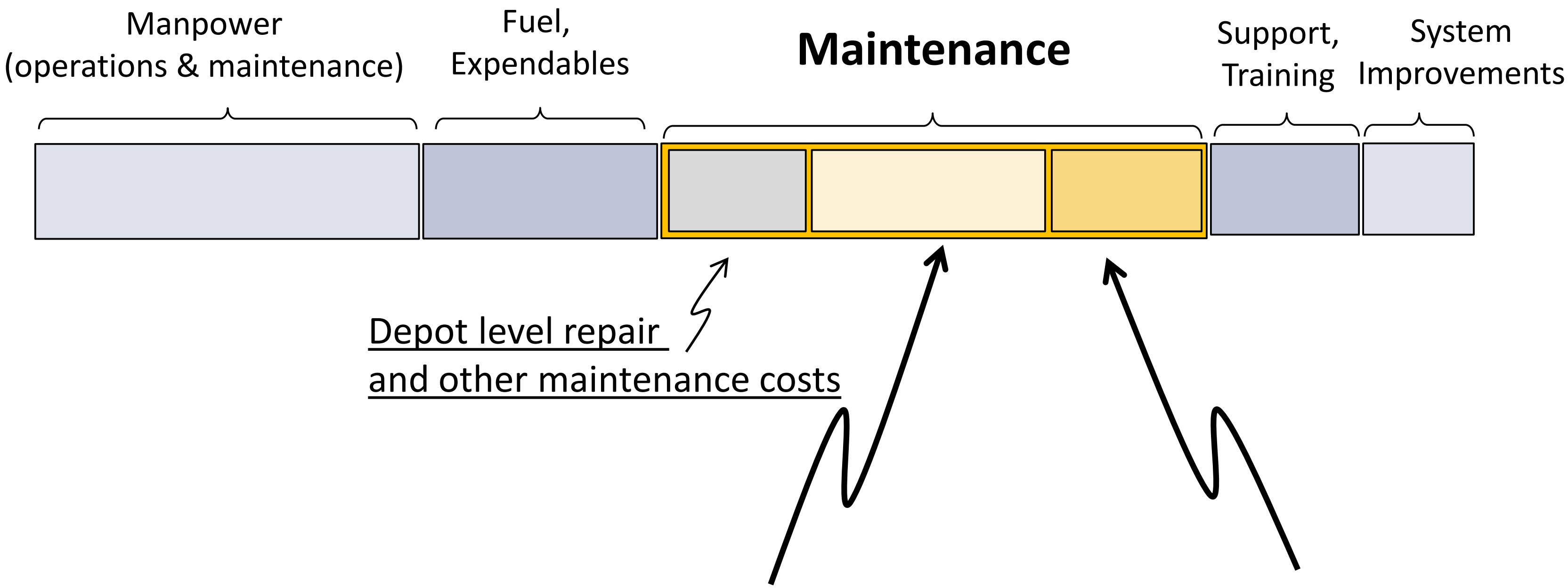

$$CPFH_{Total} = \sum_{i=1}^{n} \frac{[Replacement\ or\ Repair\ Cost]_i \times (num\ failures)_i}{Total\ Flight\ Hours}$$

CPFH = Cost per Flight Hour MFHBR = Mean Flight Hours Between Removals

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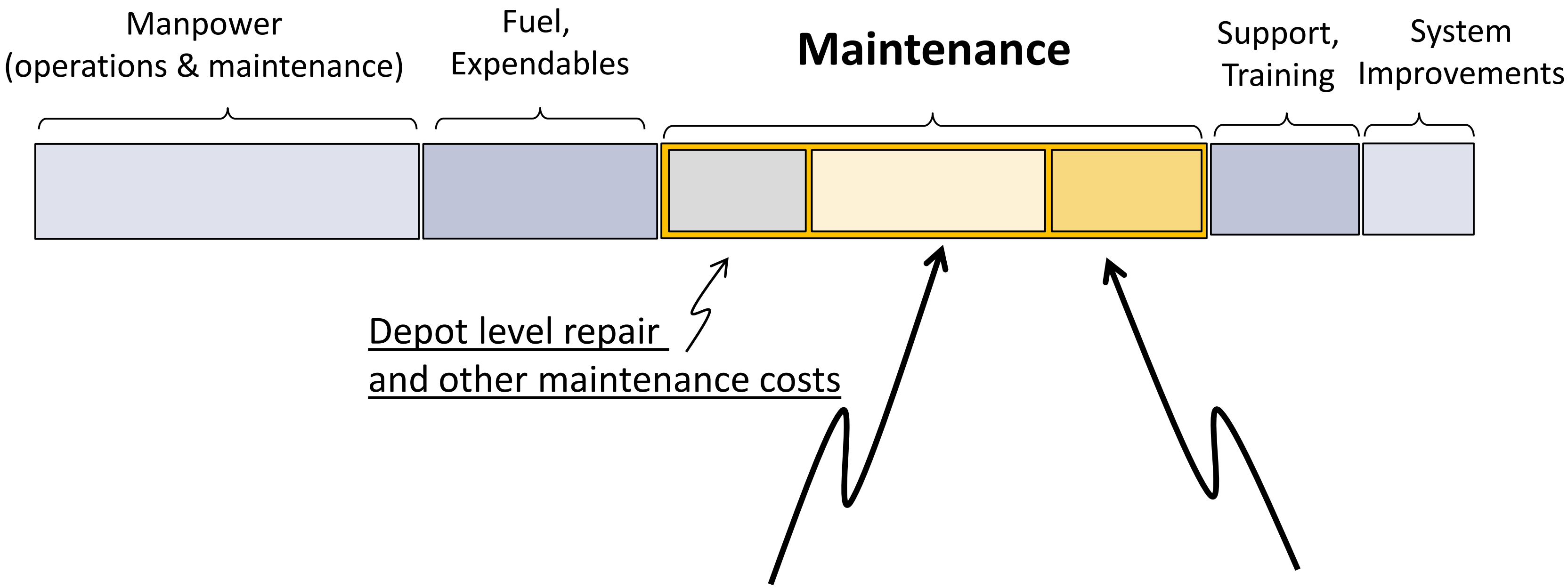
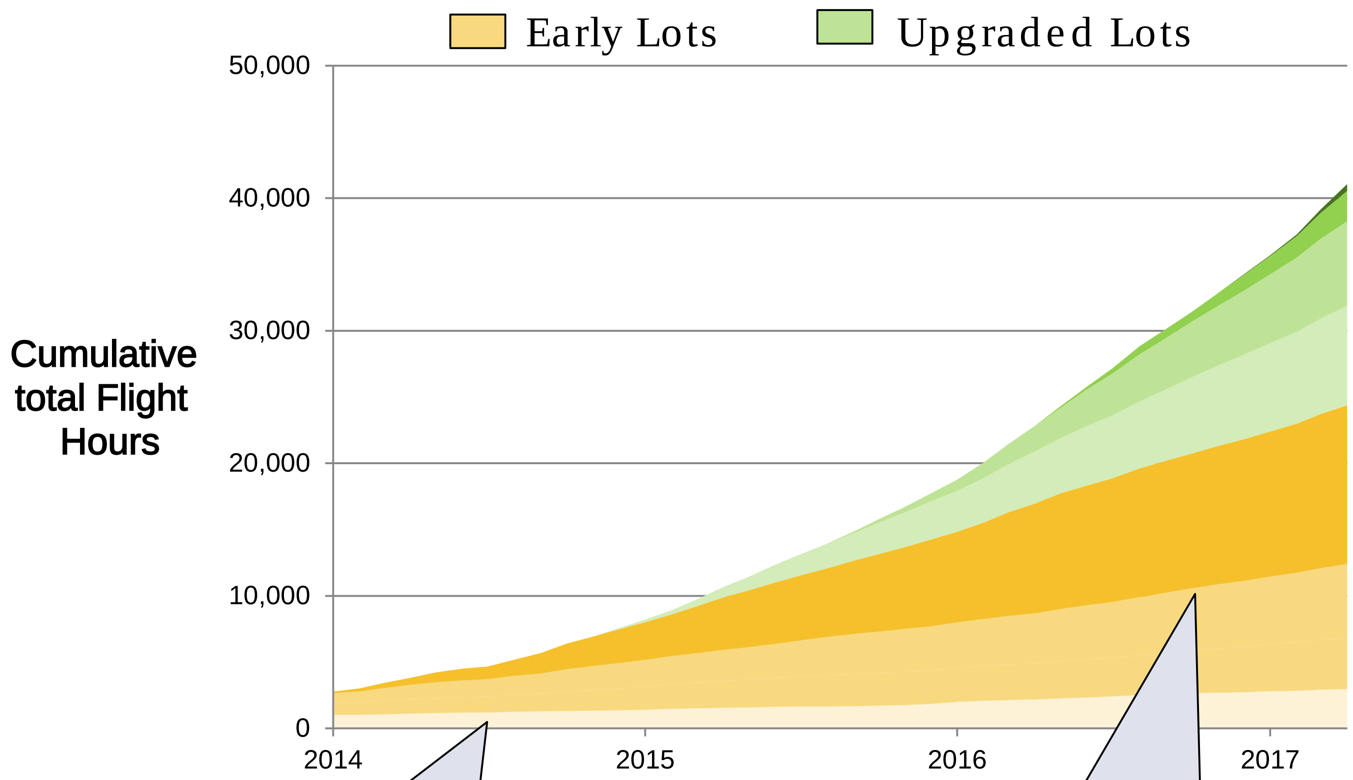


$$CPFH_{Total} = \sum_{i=1}^{n} \frac{[Replacement\ or\ Repair\ Cost]_i}{\mathbf{MFHBR}_i}$$

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

Many 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 Reliability

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

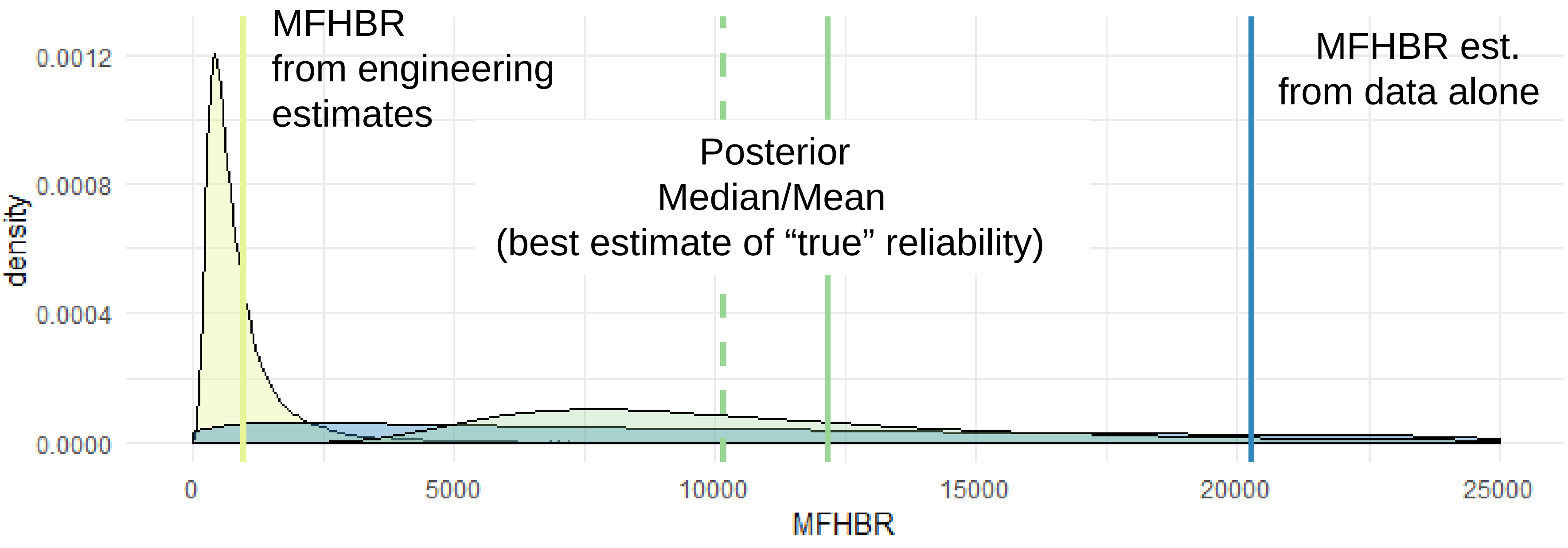
- **Likelihood Distribution:** Exponential (λ)
  - $MFHBR = \frac{1}{\lambda} = \frac{Total\ Flight\ Hours}{n}$
- **Prior Distribution:** Gamma (α, β)
  - We can use the engineering estimates to solve for α and β.
  - Inv. Gamma mean $= MFHBR_{Engineer\ Est}$
  - Inv. Gamma std. $= MFHBR_{Engineer\ Est}\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



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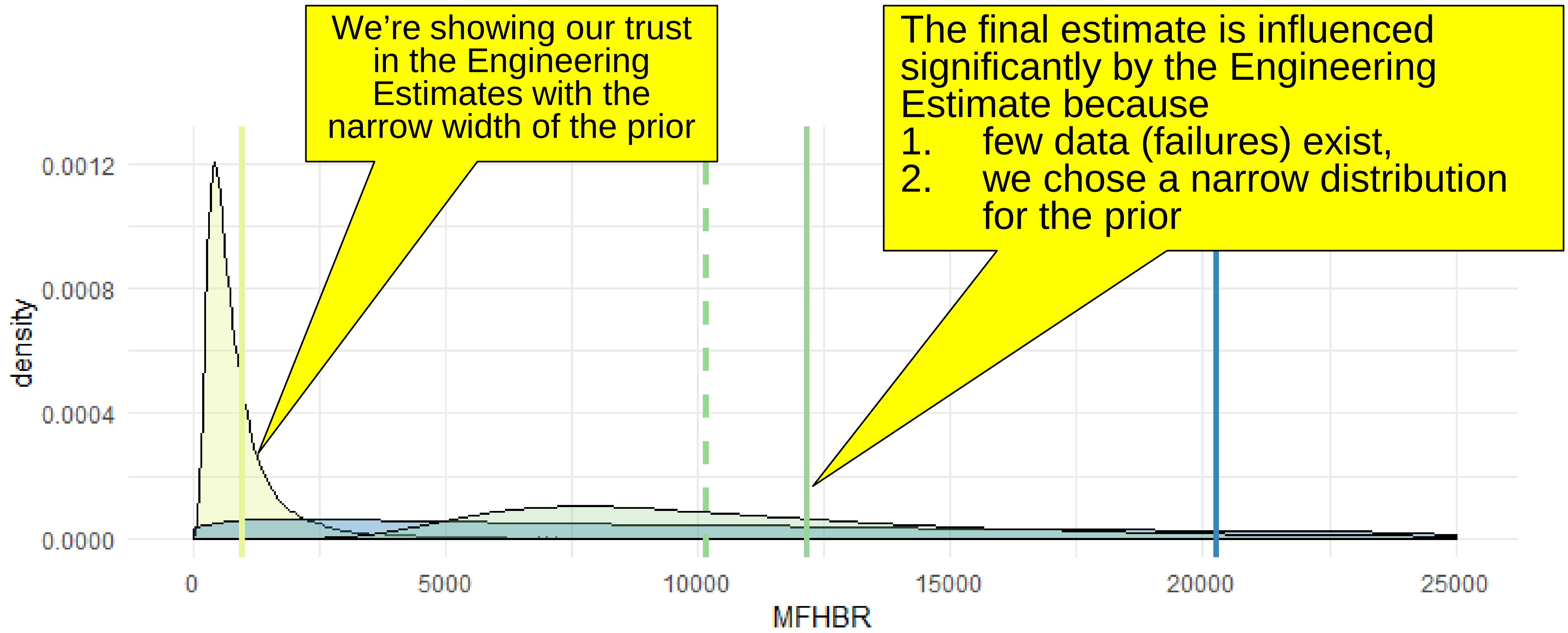
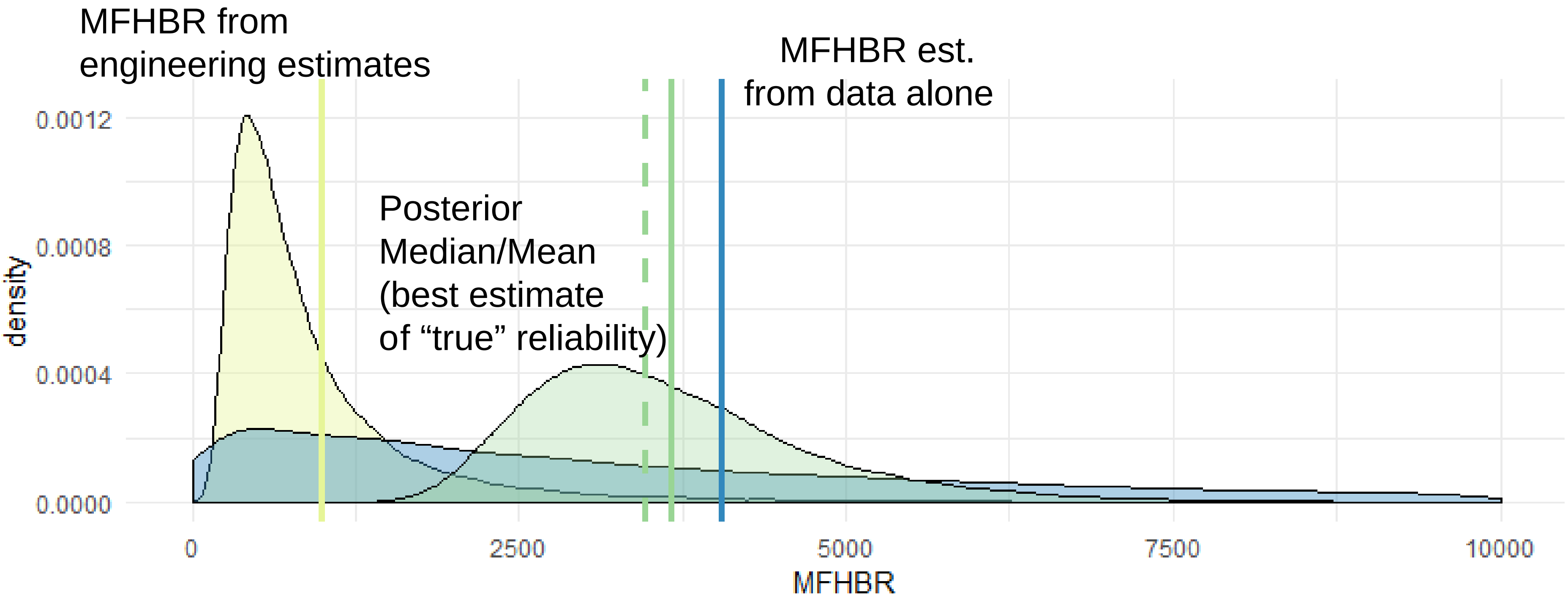


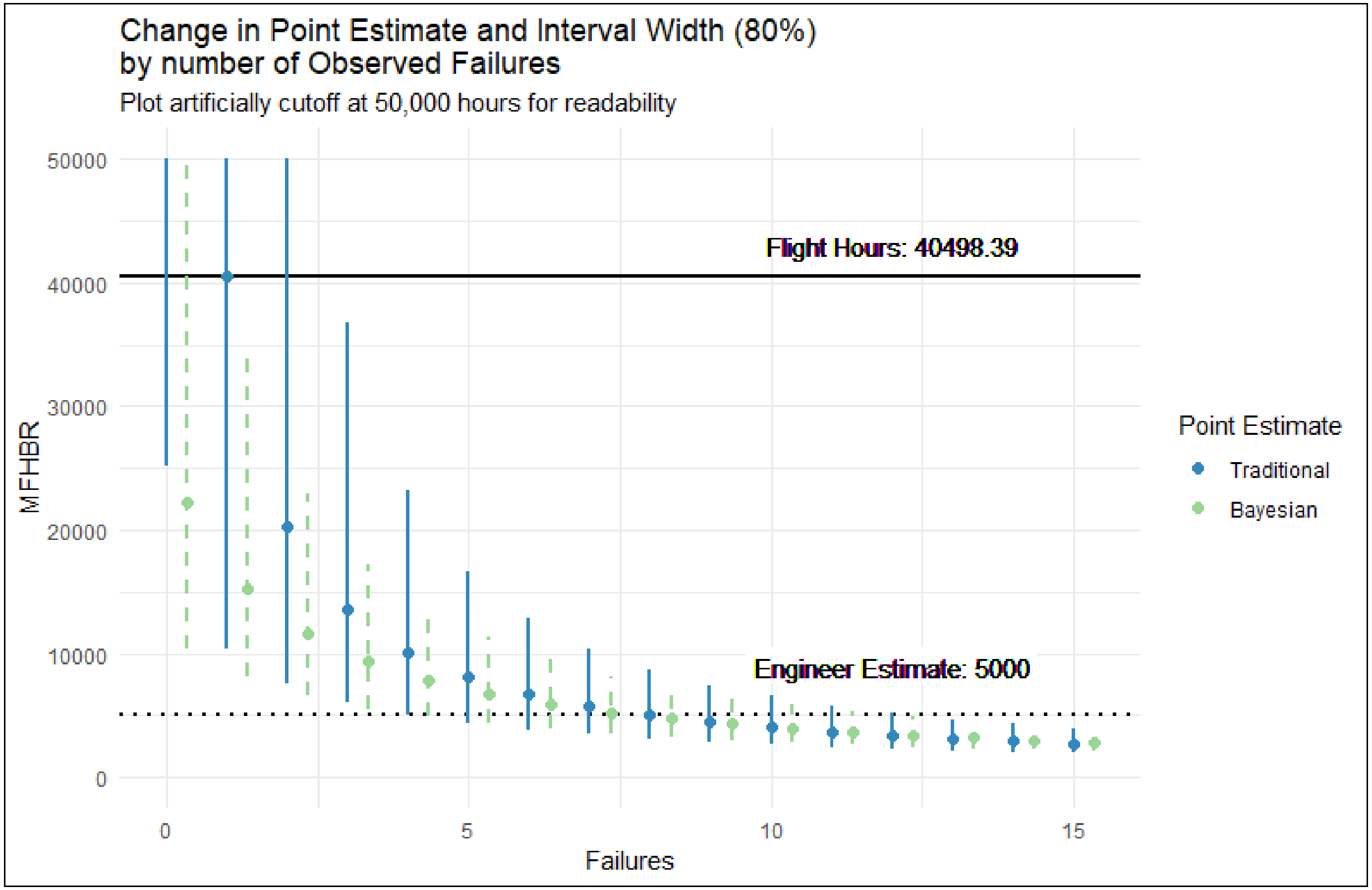
With more failure data available, the final estimate is less influenced by the MAC value

Example for Component Y:

- MAC/SPUD estimates the 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)

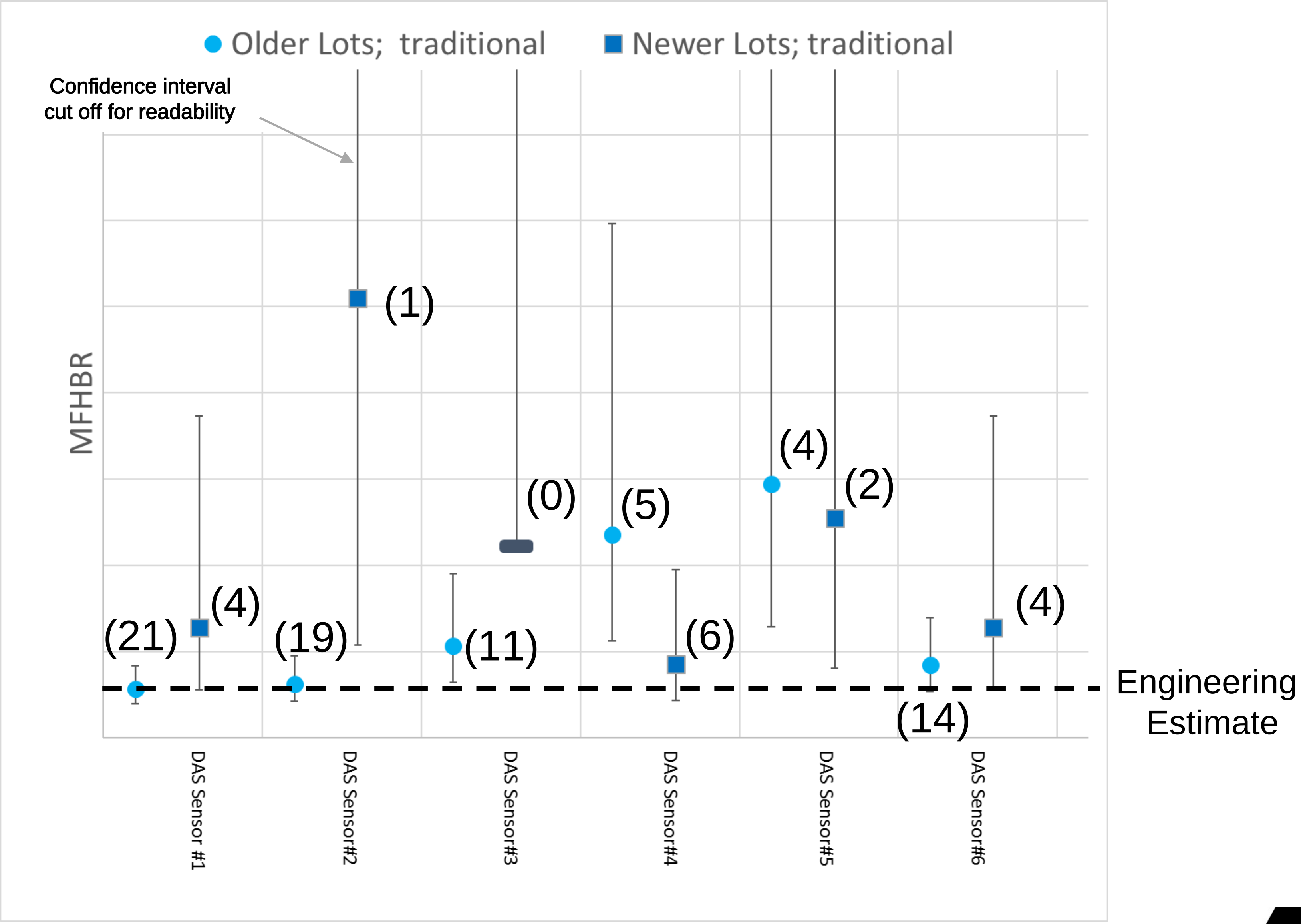
A frequent debate:
How do we estimate MFHBR for a new configuration?

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

	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 <u>starting point</u>, 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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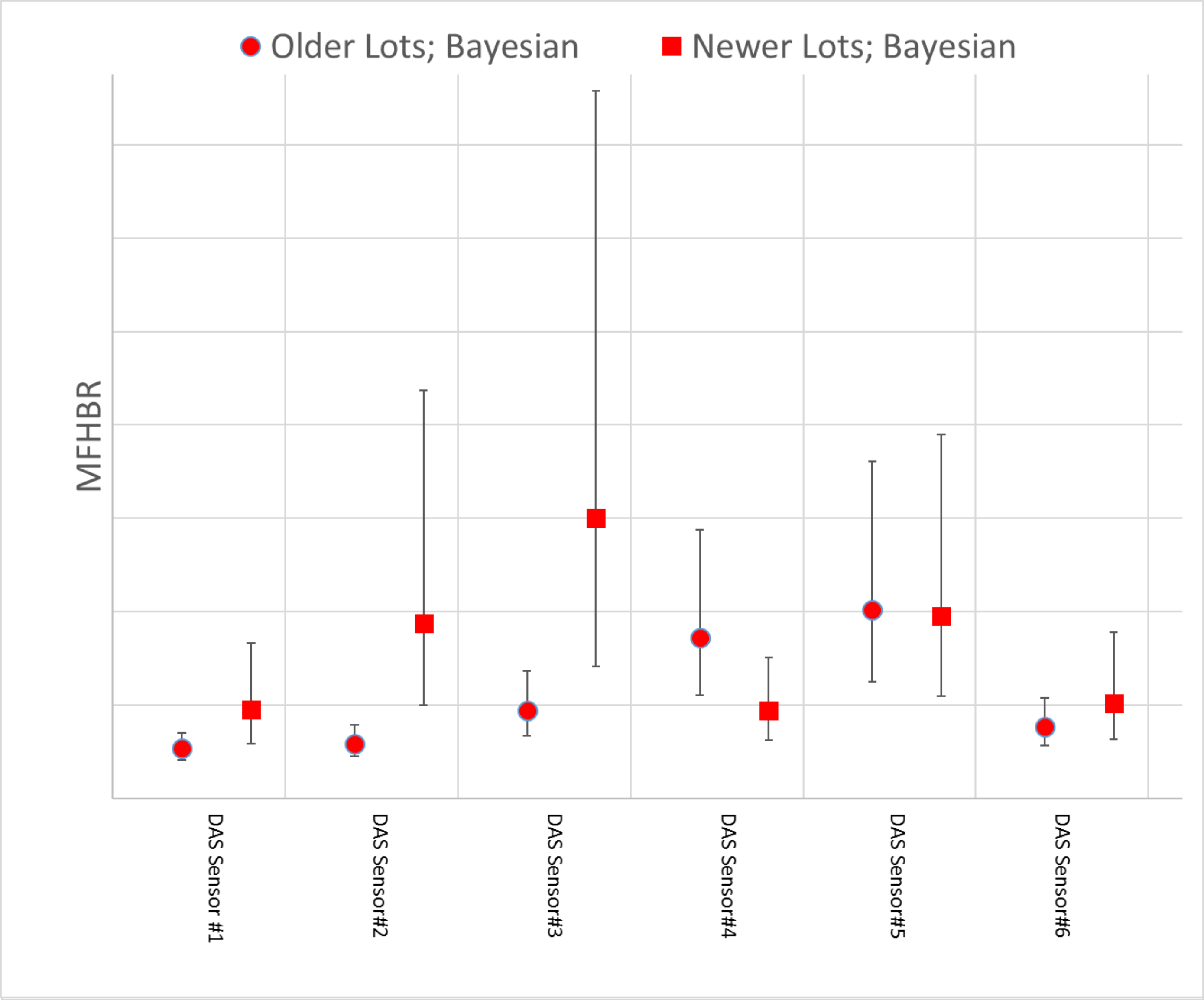

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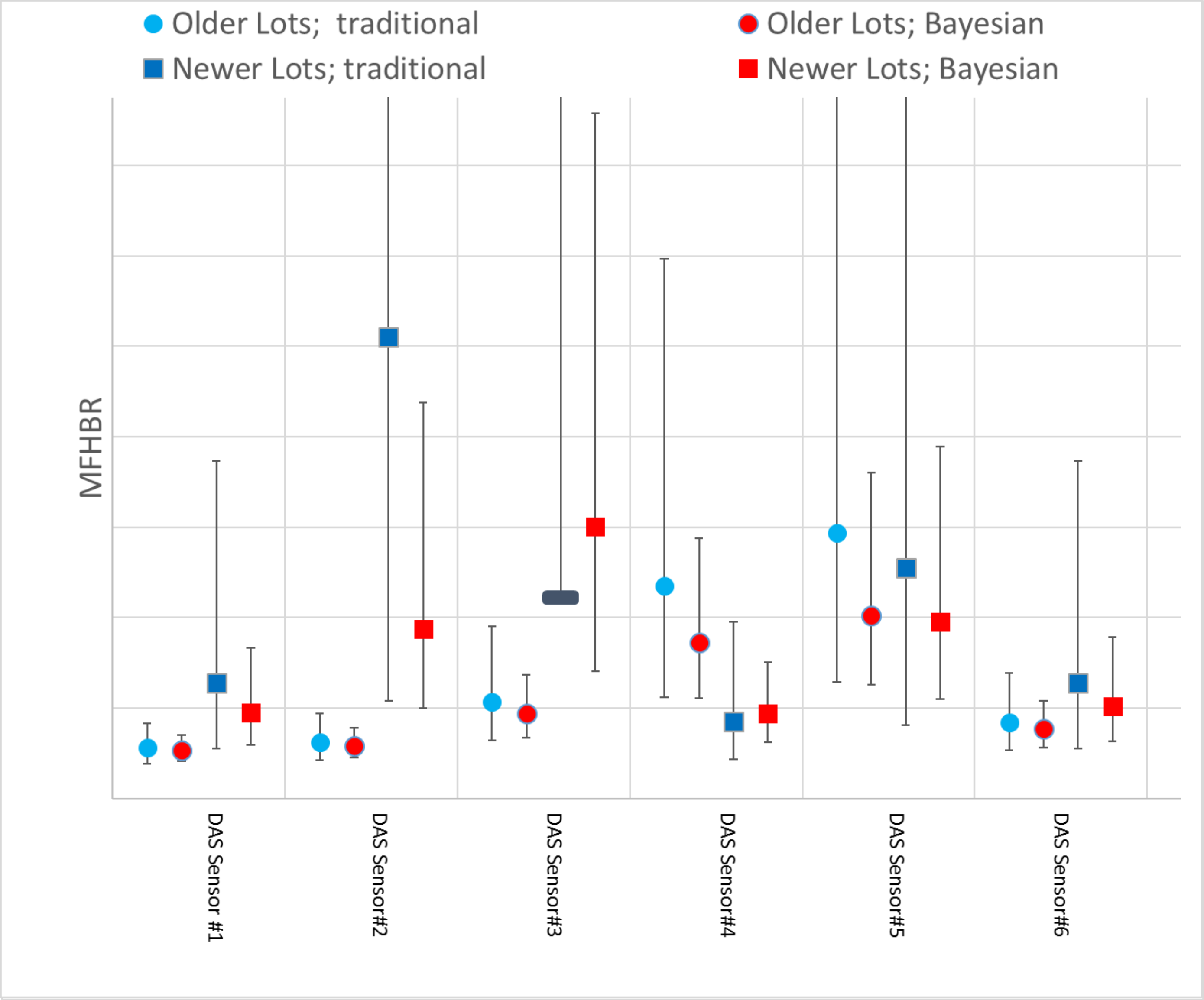

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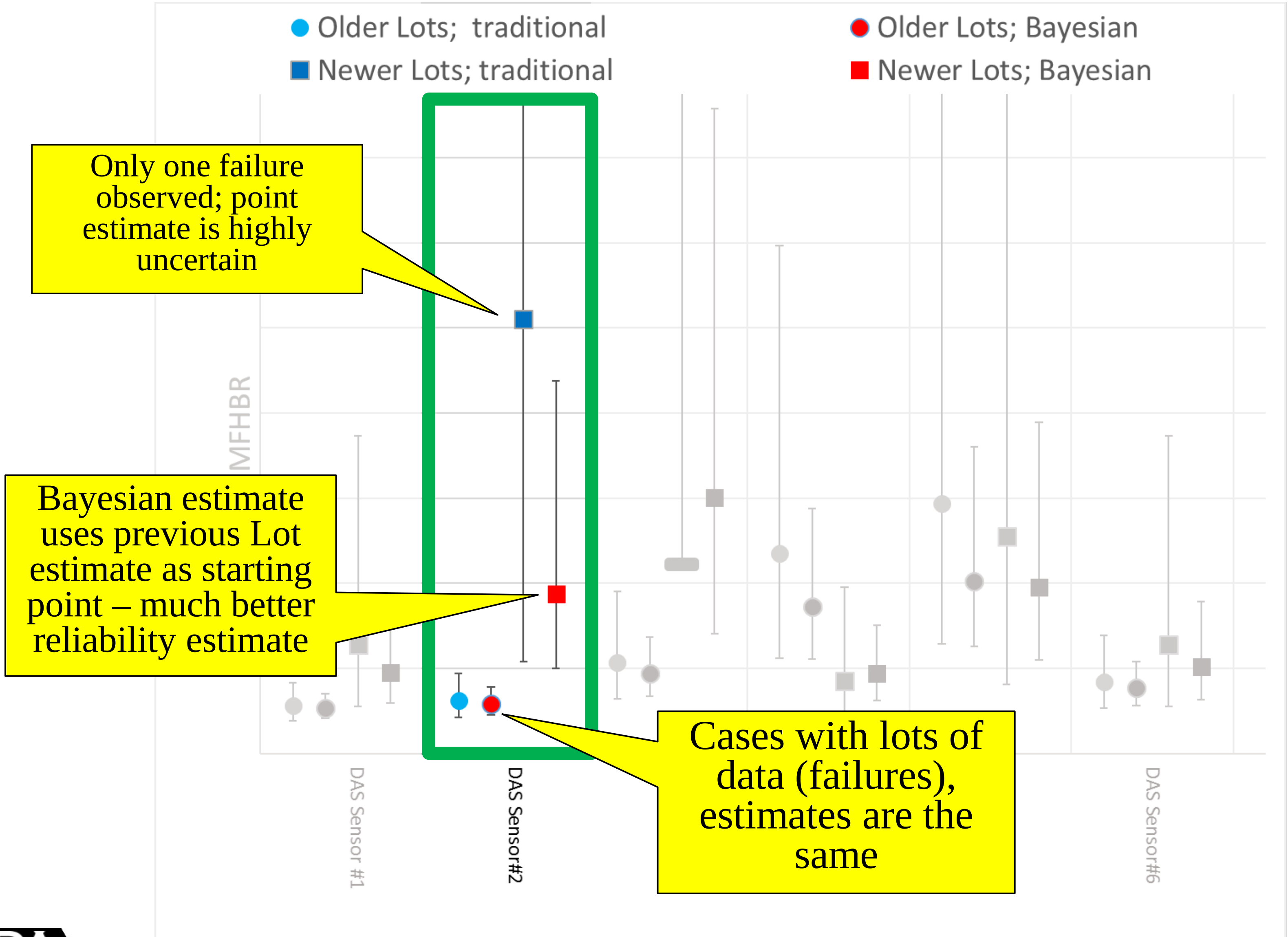

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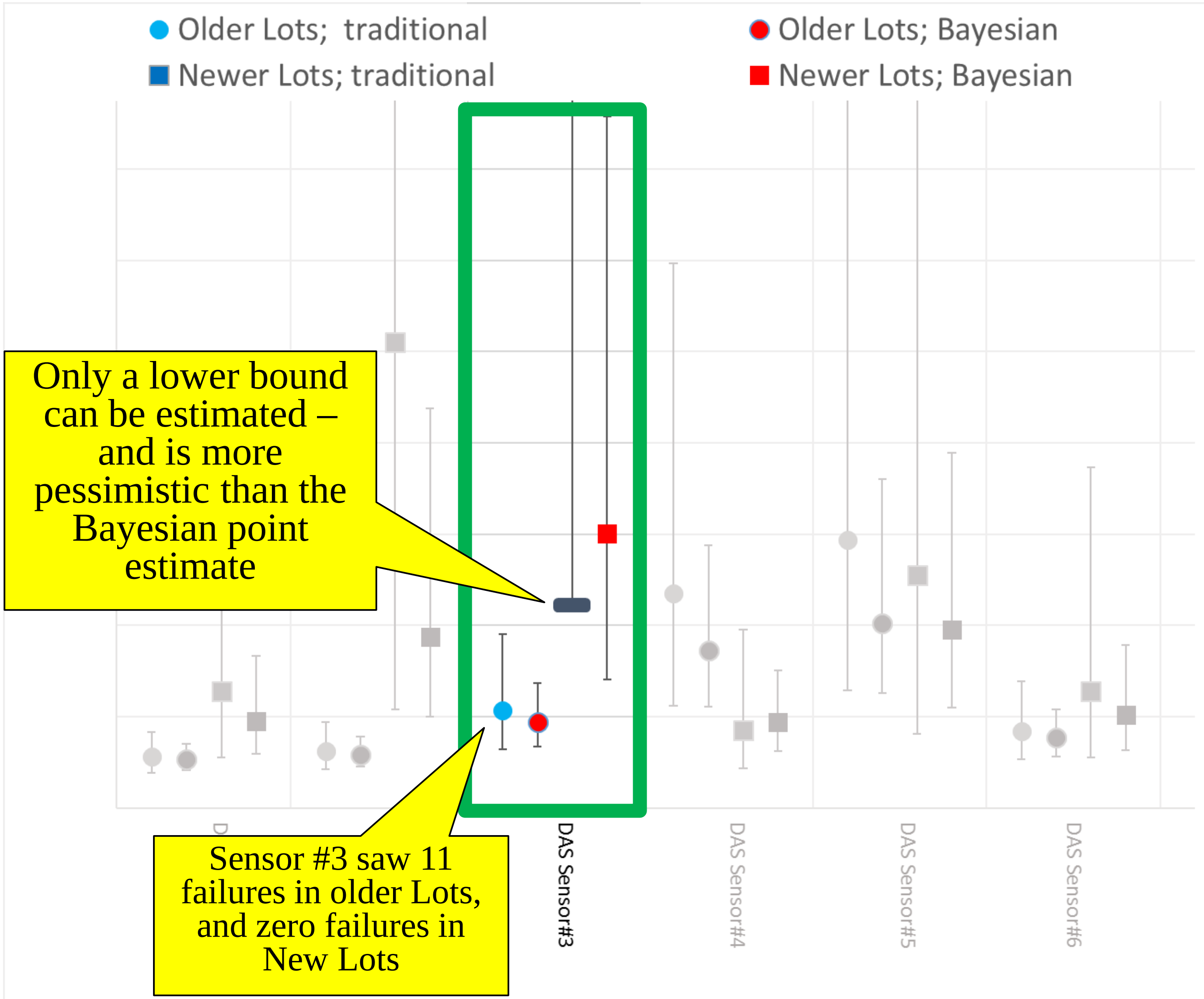

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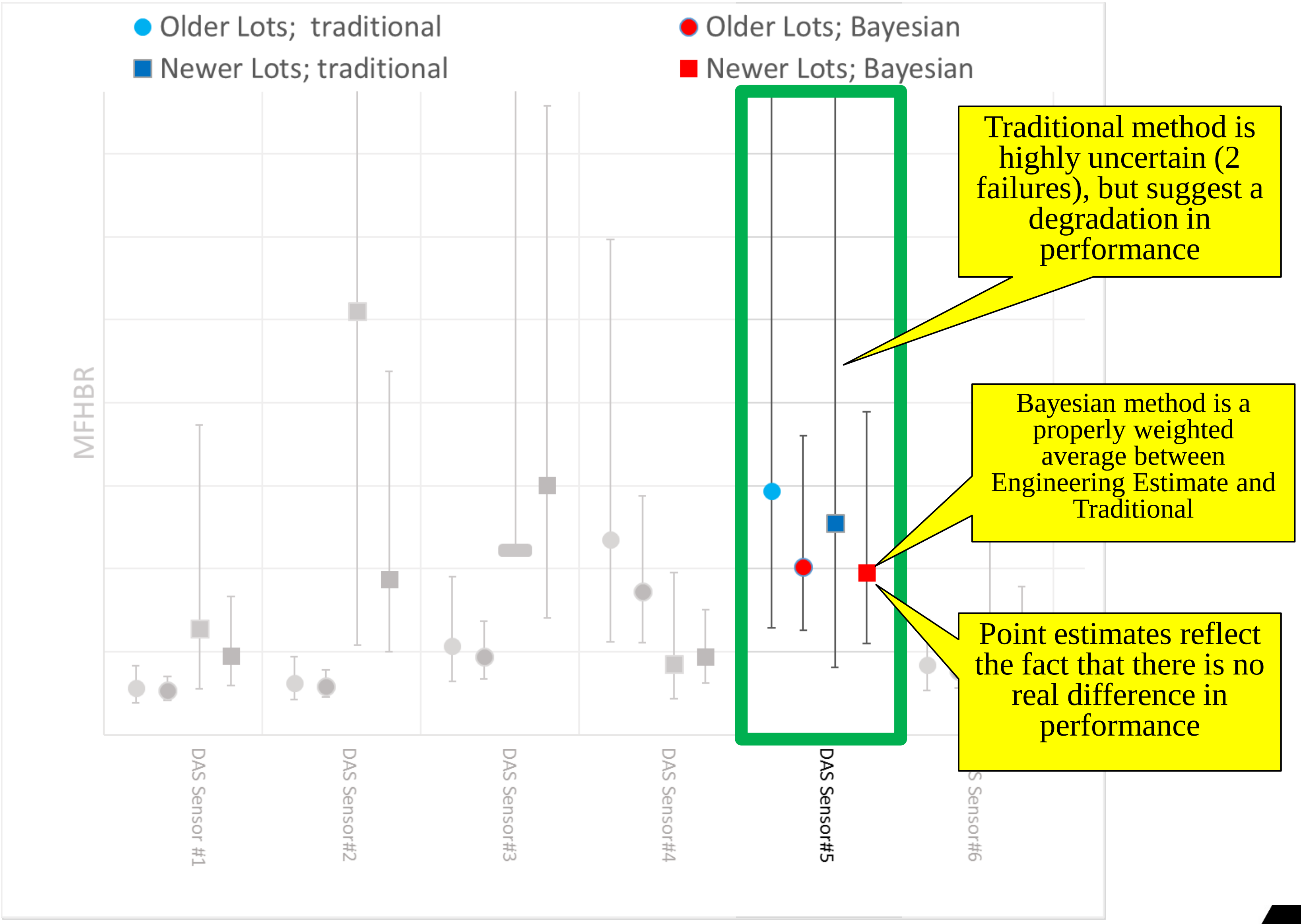

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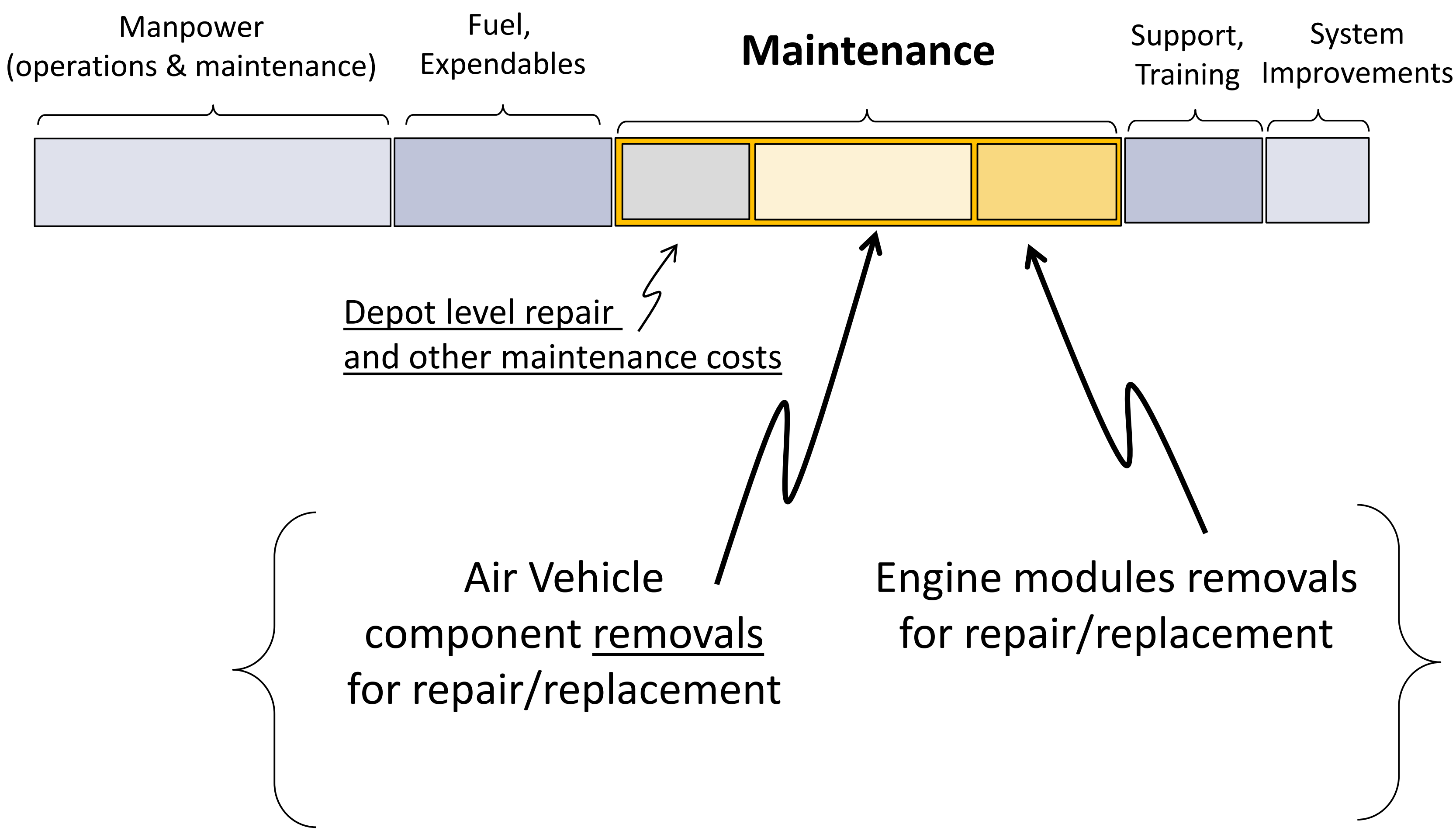
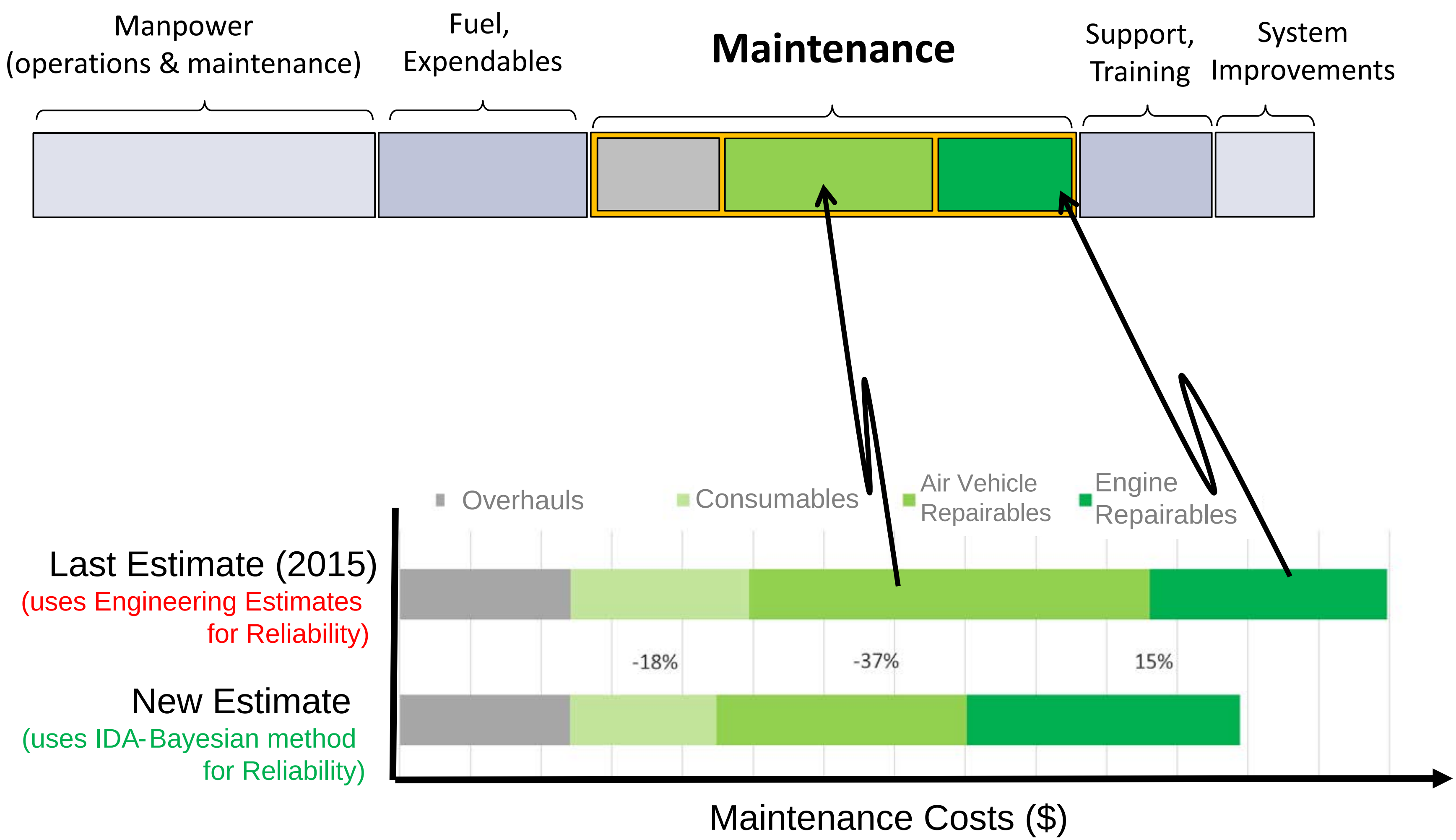


Bayesian Reliability results in a more informed estimate of maintenance costs



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!)