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Rationale for component testing in fuel cell vehicles

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Statistical formulation

Standard Weibull equation:

$$R(t_d) = \exp\left[-\left(\frac{t_d}{\eta}\right)^{\beta}\right]$$

Weibayes 'zero-failure' formulation:

$$\frac{T_i}{t_d} = \left[\frac{-1}{N \times \ln\big(R(t_d)\big)}\right]^{1/\beta}$$

T_i	test time (cycles)
t_d	design life (cycles)
$R(t_d)$	Reliability at design life design
N	number of samples
β	Weibull shape parameter

Component testing

Standard Weibull equation:

$$R(t_d) = \exp\left[-\left(\frac{t_d}{\eta}\right)^{\beta}\right]$$

Weibayes 'zero-failure' formulation:

$$\frac{T_i}{t_d} = \left[\frac{-1}{N \times \ln\left(R(t_d)\right)}\right]^{1/\beta}$$

Multiplier for testing = 1.96

$R(t_d)$ = 99% (reliability assumption)

N = 3 (# of tests)

β = 5.2

Component testing

Standard Weibull equation:

$$R(t_d) = \exp\left[-\left(\frac{t_d}{\eta}\right)^{\beta}\right]$$

Weibayes 'zero-failure' formulation:

$$\frac{T_i}{t_d} = \left[\frac{-1}{N \times \ln\left(R(t_d)\right)}\right]^{1/\beta}$$

$R(t_d)$ = 95% (reliability assumption)

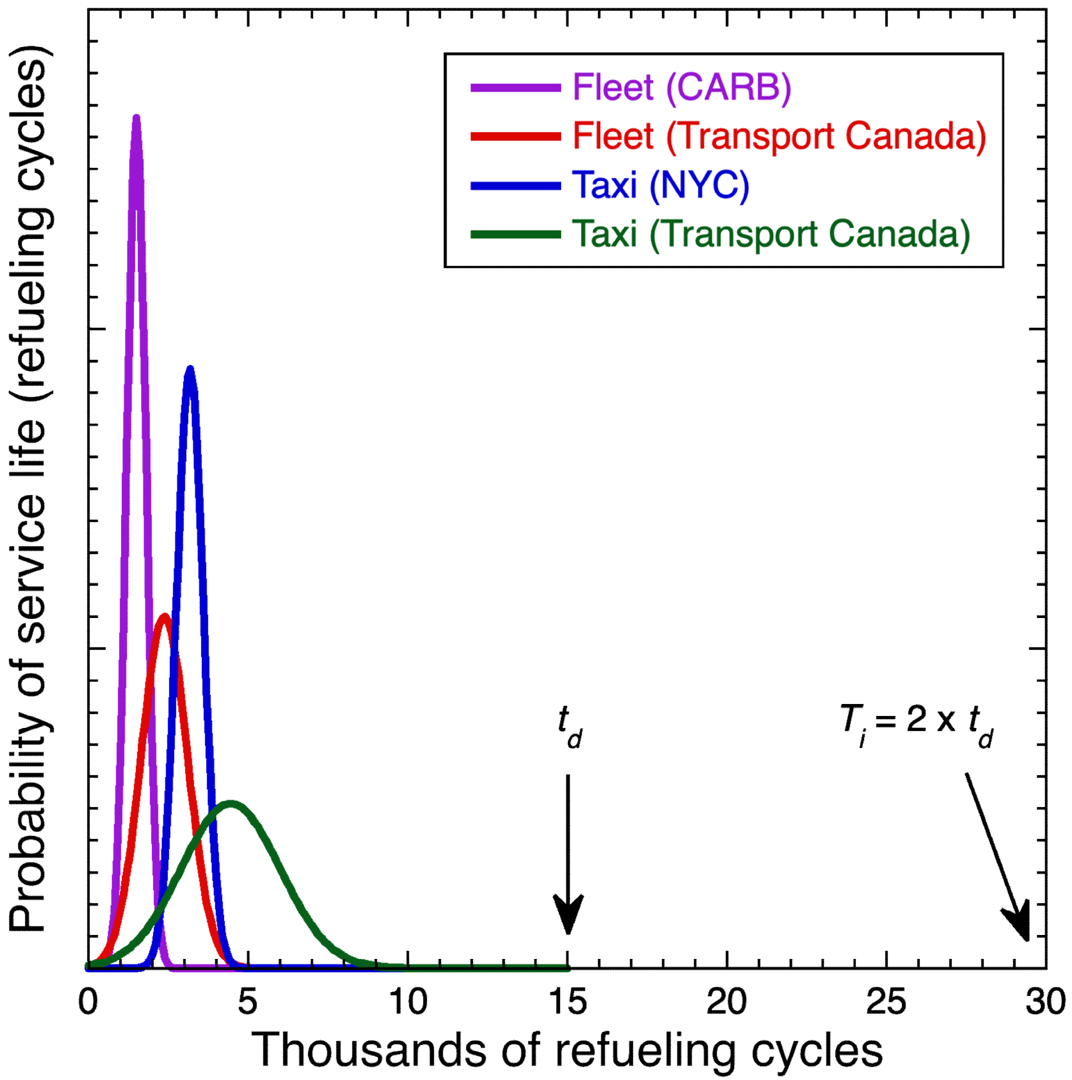
N = 3 (# of tests)

β = 2.5

Multiplier for testing = 2.11

(or if N = 5, the multiplier drops to 1.72)

Consider refueling cycles from ECE/TRANS/WP.29/GRSP/2022/16



Light duty refueling scenarios: para. 76

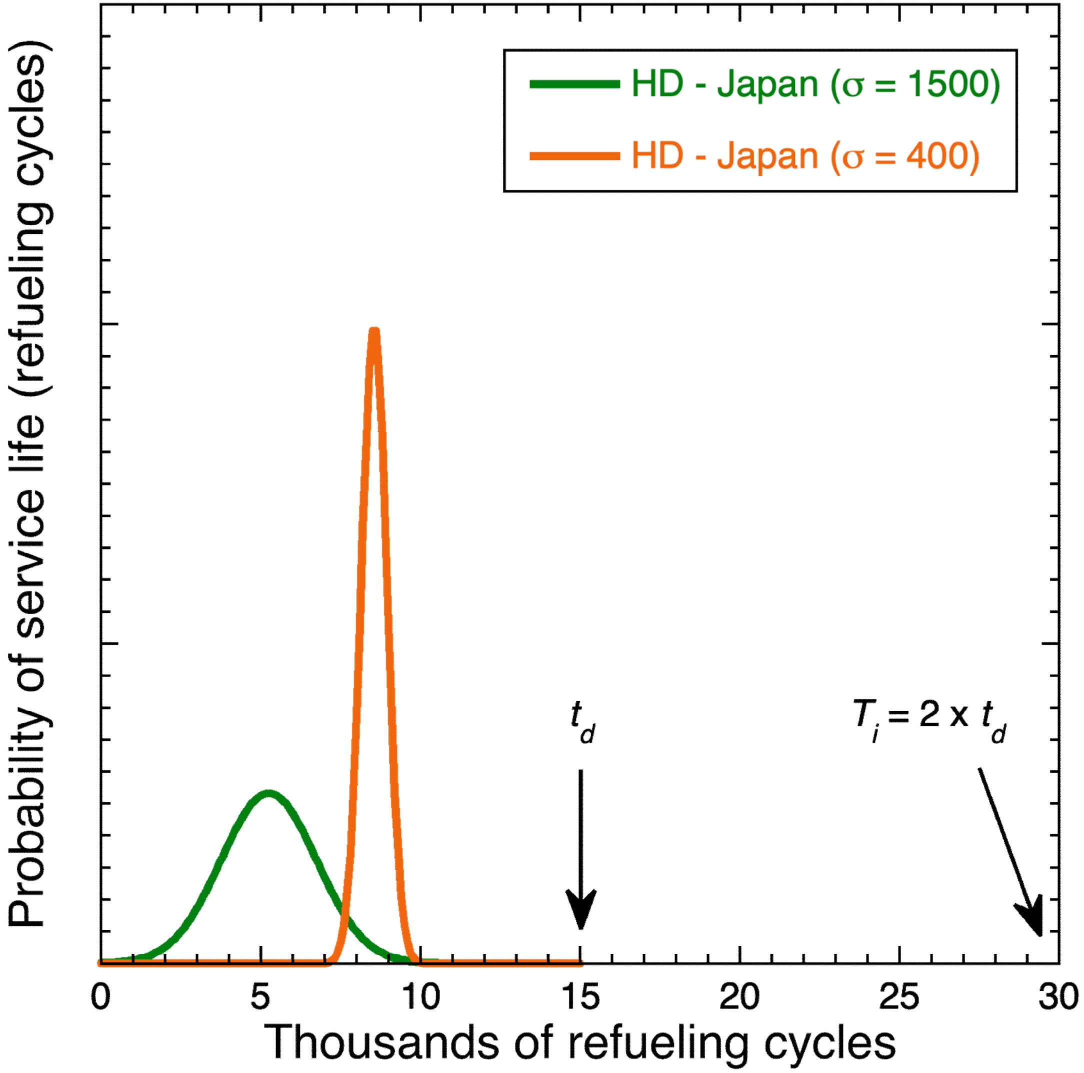
- Fleet (CARB) = 1,200 – 1,800
- Fleet (Transport Canada) = 1,650 – 3,100
- Taxi (NYC) = 2,750 – 3,600
- Taxi (Transport Canada) = 2,900 – 6,000

These numbers are assumed to represent $\mu \pm \sigma$
(mean ± one standard deviation on a normal distribution)

$t_d = \mu + 6 \text{ to } 45\ \sigma$
$T_i = \mu + 16 \text{ to } 95\ \sigma$

T_i test time (cycles)
t_d design life (cycles)

Consider refueling cycles from ECE/TRANS/WP.29/GRSP/2022/16



Heavy duty refueling scenarios: para. 78

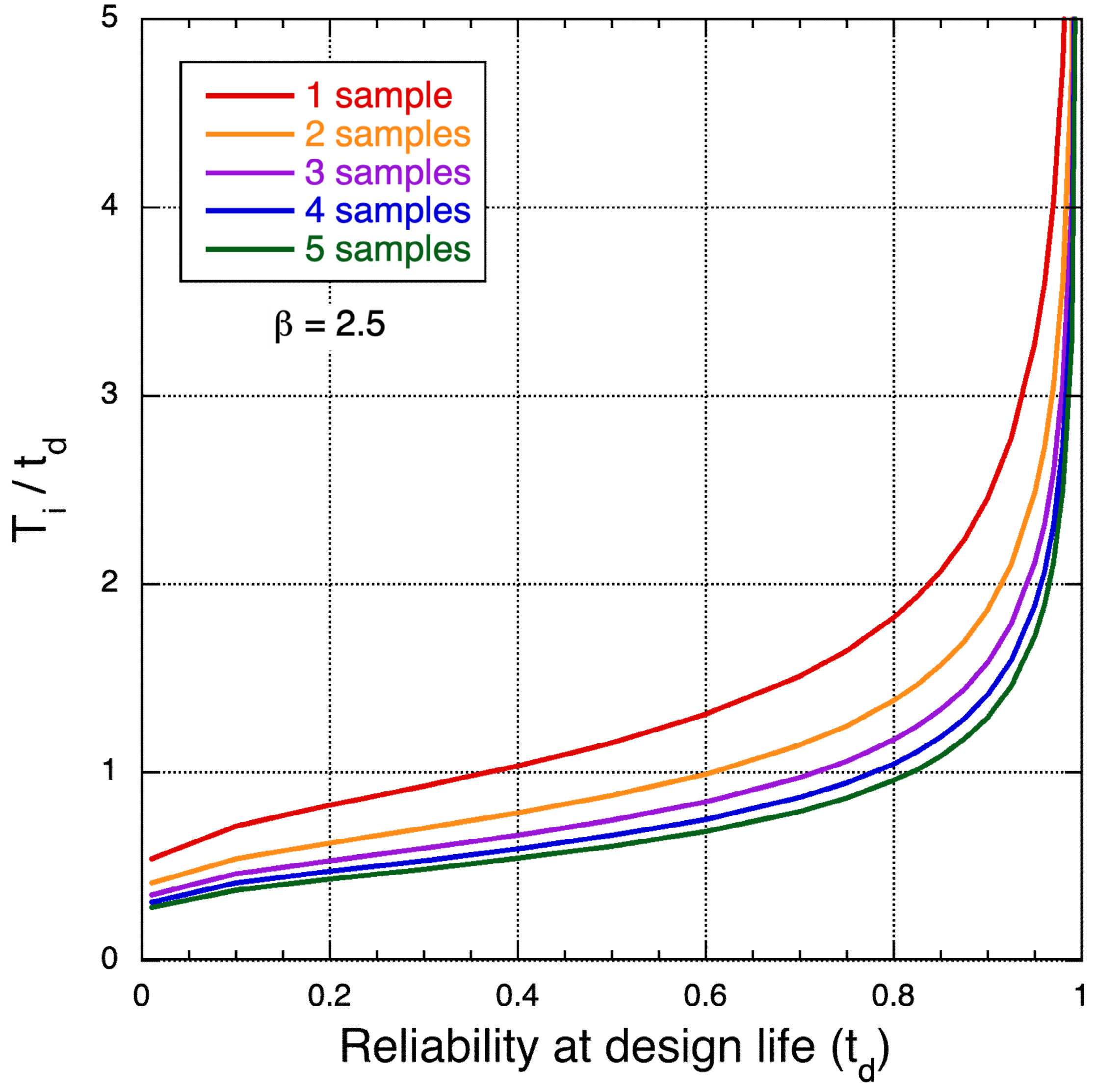
- HD Commercial (Japan) = 9,750
- LD commercial (Japan) = 7,440
- HD Commercial (Germany) = 6,390
- Semi-trailer truck(Germany) = 7,987

Distributions are not provided, therefore:

- assume worst-case from LD: σ = 1500
  - Since probability is driven by standard deviation (σ)
- assume lifetime = $\mu + 3\sigma$
  - Since values are considered lifetime, they should be upper end of distribution

Worst case: $t_d > \mu + 6\,\sigma$
$T_i > \mu + 16\,\sigma$

Example of reliability for different number of test articles and a conservative β value



$$\frac{T_i}{t_d} = \left[\frac{-1}{N \times \ln\left(R(t_d)\right)}\right]^{1/\beta}$$

If the goal is 80% reliability at design life of t_d:

- **<u>One sample</u>** must be tested to $T_i = t_d \times 1.82$
- **<u>Five samples</u>** achieve this goal at $T_i = t_d \times 0.96$

Summary

- Weibayes analysis shows that to achieve 95% reliability at the design life with extended life testing of 3 samples (and assuming β = 2.5):

$$T_i = 2.11 \, x \, t_d$$

  - In other words, a 'safety factor' of 2x on number of cycles in component evaluation with achieve 95% reliability at design life (t_d)
  - β = 2.5 is relatively conservative; higher β results in higher reliability

- However, considering the predicted number of refuelings, design life (t_d) of 15,000 cycles is >6 standard deviations more than the mean (cycles)

Interpretation:	component testing at 15,000 cycles (1x) is sufficient for exceptional reliability (refueling cycles)