Asset Management Using Failure Forecasting and Statistical Assessment of Diagnostic Testing

Miroslav M. Begovic
School of ECE, Georgia Institute of Technology

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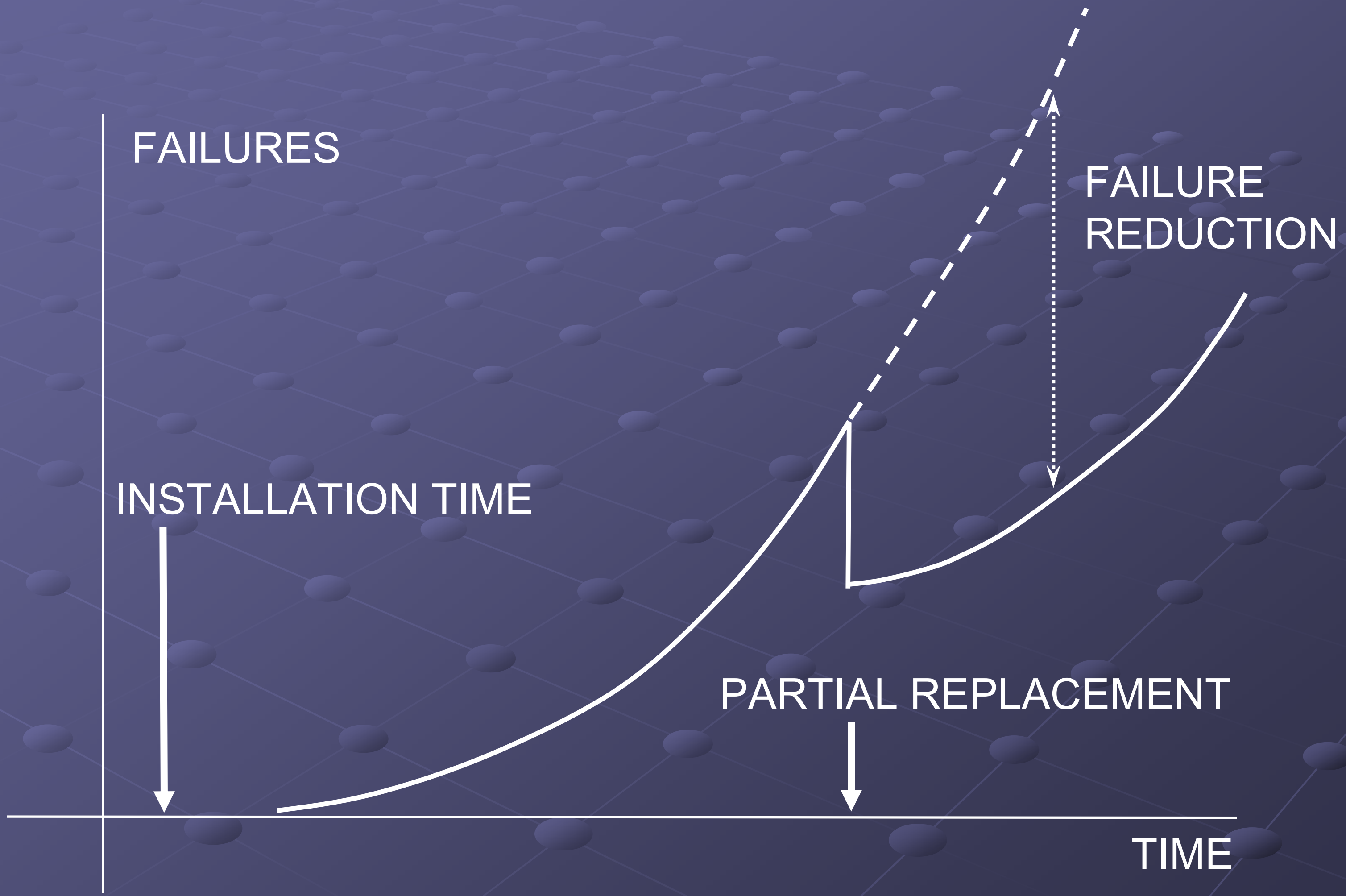
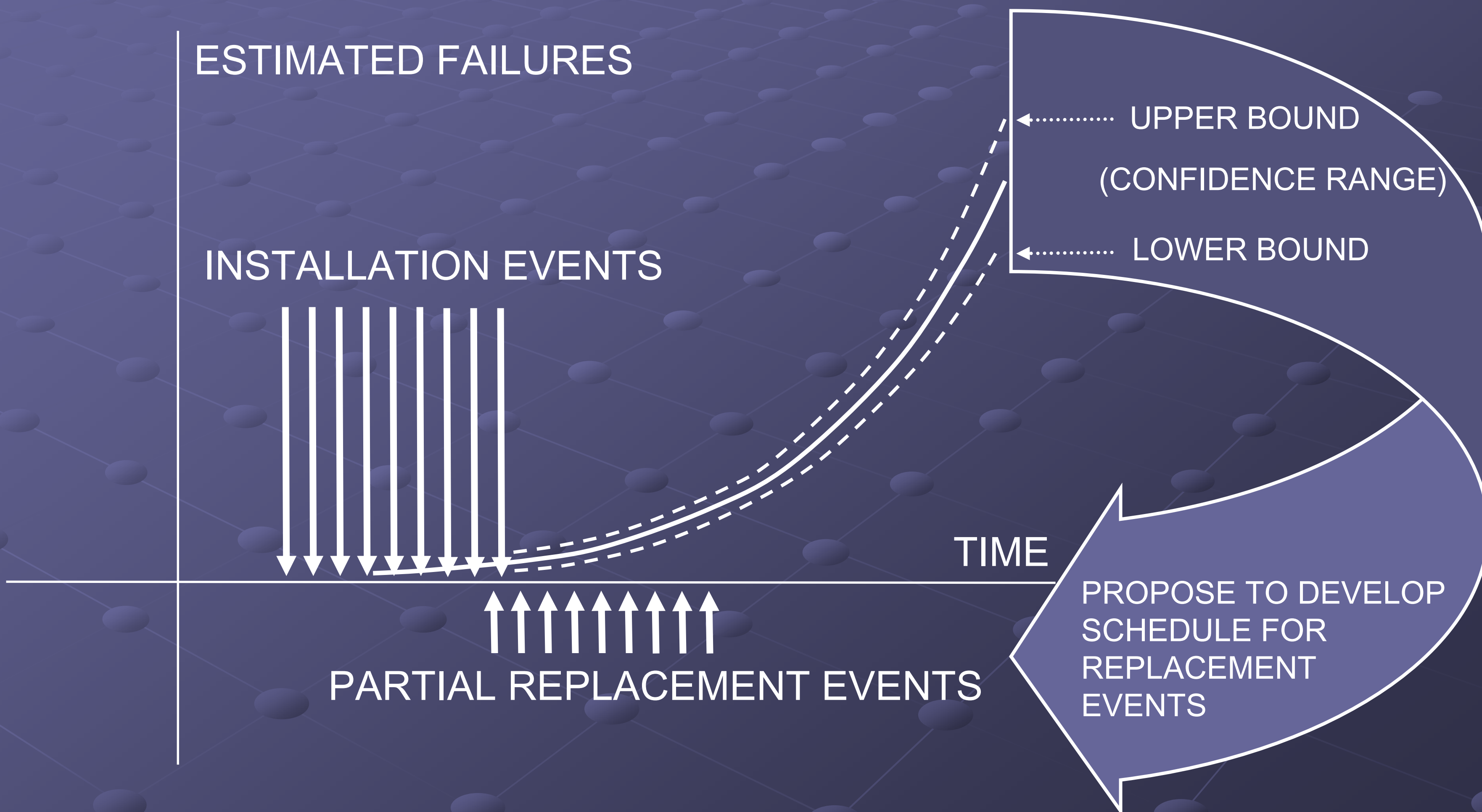
Background/Problem Statement

- Most utilities have incomplete failure data on various components, such as cables, switchgear, etc.
- Framework: a software-based algorithm to estimate future failures based on data obtained from incomplete failure information.
- The optimal *replacement* rate needed to maintain failures at a specified *failure rate* is sought.
- Optimal failure rate estimation will yield the lowest replacement and maintenance budget required to meet the desired failure performance

Effect of Replacements on Failure Rates



Estimation and Control of Failures in Composite Populations



Preliminaries

- If *p*(*t*) is the pdf of the time to failure *t* of a single component, the probability of that component failing before time *t* is given by

$$P(t) = \int_0^t p(u)\,du$$

- Assuming Weibull distribution for *p*(*t*) and population of *N* identical components, the *pdf* of a component of that population failing before time *t* is given by

$$p_0(t) = N\beta\alpha^{-\beta} t^{\beta-1} e^{-(t/\alpha)^{\beta} N}, \quad t \geq 0.$$

Preliminaries (cont.)

- The expected value of *T* (the time to failure of a single component) is

$$E(T) = \alpha\Gamma\left(\frac{1}{\beta}+1\right)$$

- The expected value of *T* (the time to failure of a single component) in a population of N identical components is

$$E(T_0) = \frac{\alpha}{N^{1/\beta}}\Gamma\left(\frac{1}{\beta}+1\right)$$

Failure Rates

The overall failure rate will be

$$f_0(t) = \frac{p_0(t)}{1 - P_0(t)}, \qquad t \geq 0$$

In terms of the original α and *N*

$$f_N(t) = N\beta\alpha^{-\beta}t^{\beta-1}, \qquad t \geq 0$$

Which will produce linear growth compared to the aging of a single component

$$p(t) = Wei(\alpha, \beta) = \beta\alpha^{-\beta}t^{\beta-1}e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \qquad t \geq 0$$

$$f(t) = \beta\alpha^{-\beta}t^{\beta-1}, \qquad t \geq 0$$

Formulation of the Failure Model

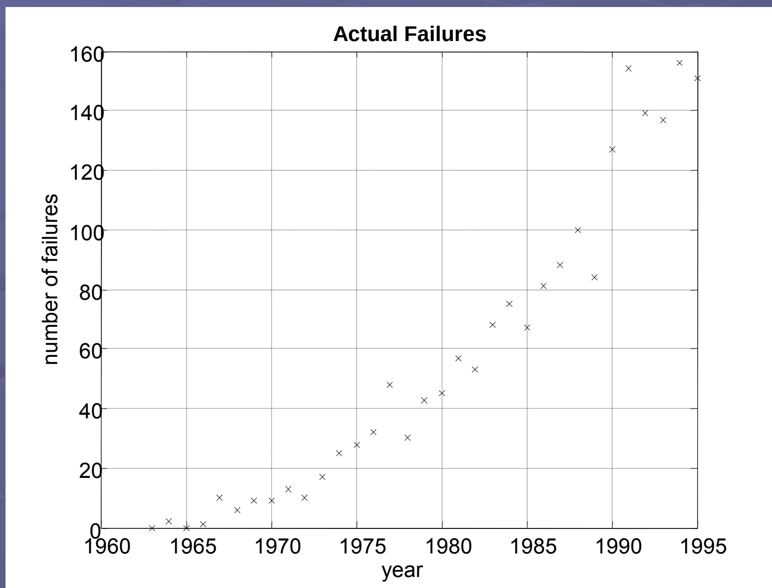
$$f(t) = X \cdot K \cdot (t - g)^b$$

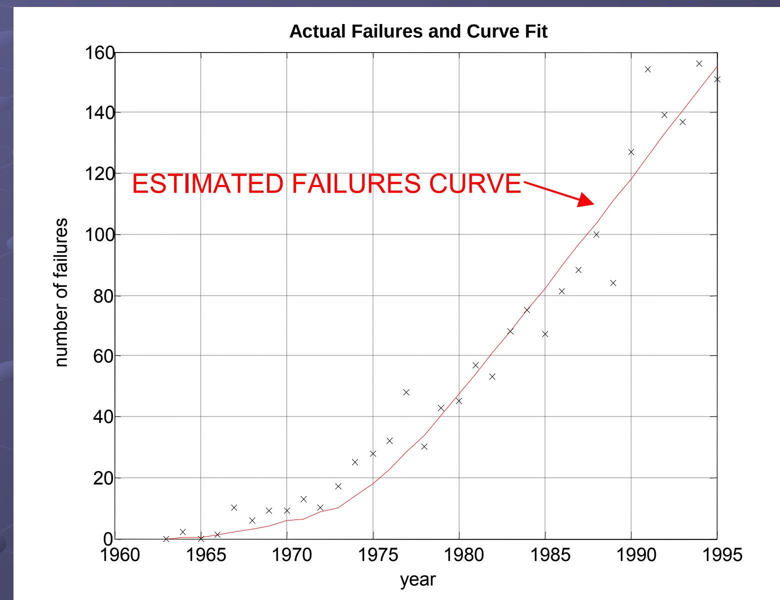
Parameters K,b,g represent the description (model) of the failures for population X (or N, if we deal with the discrete components)

When there are *multiple* populations X_i installed in years i = 0, 1, 2, …, k, the *cumulative* failure model F(*t,g,b,K*) becomes a sum:

$$F(t, g, b, K) = \sum_{i=0}^{k} X_i \cdot K \cdot (t - g - i)^b$$

Methodology for Identification of Statistical Coefficients

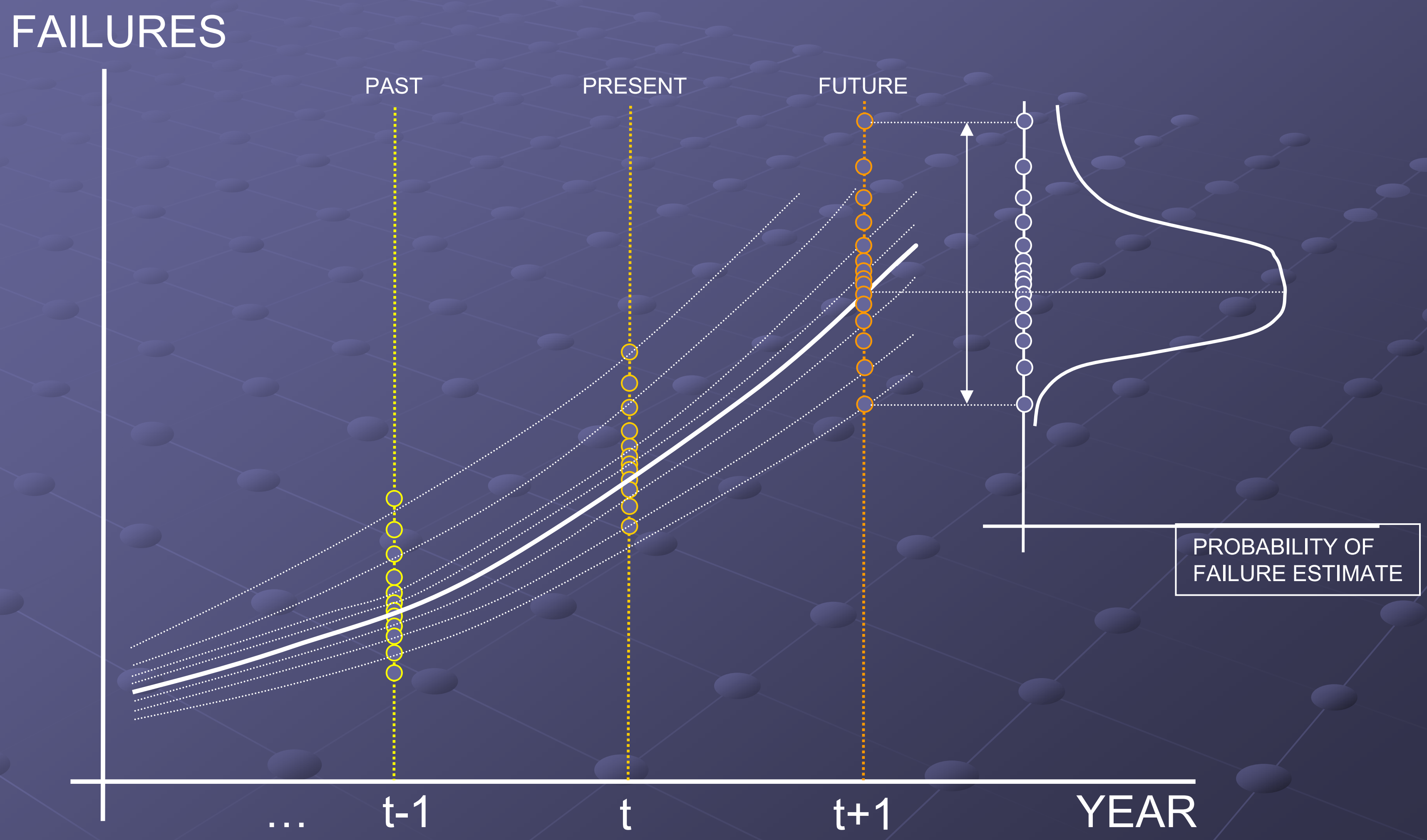




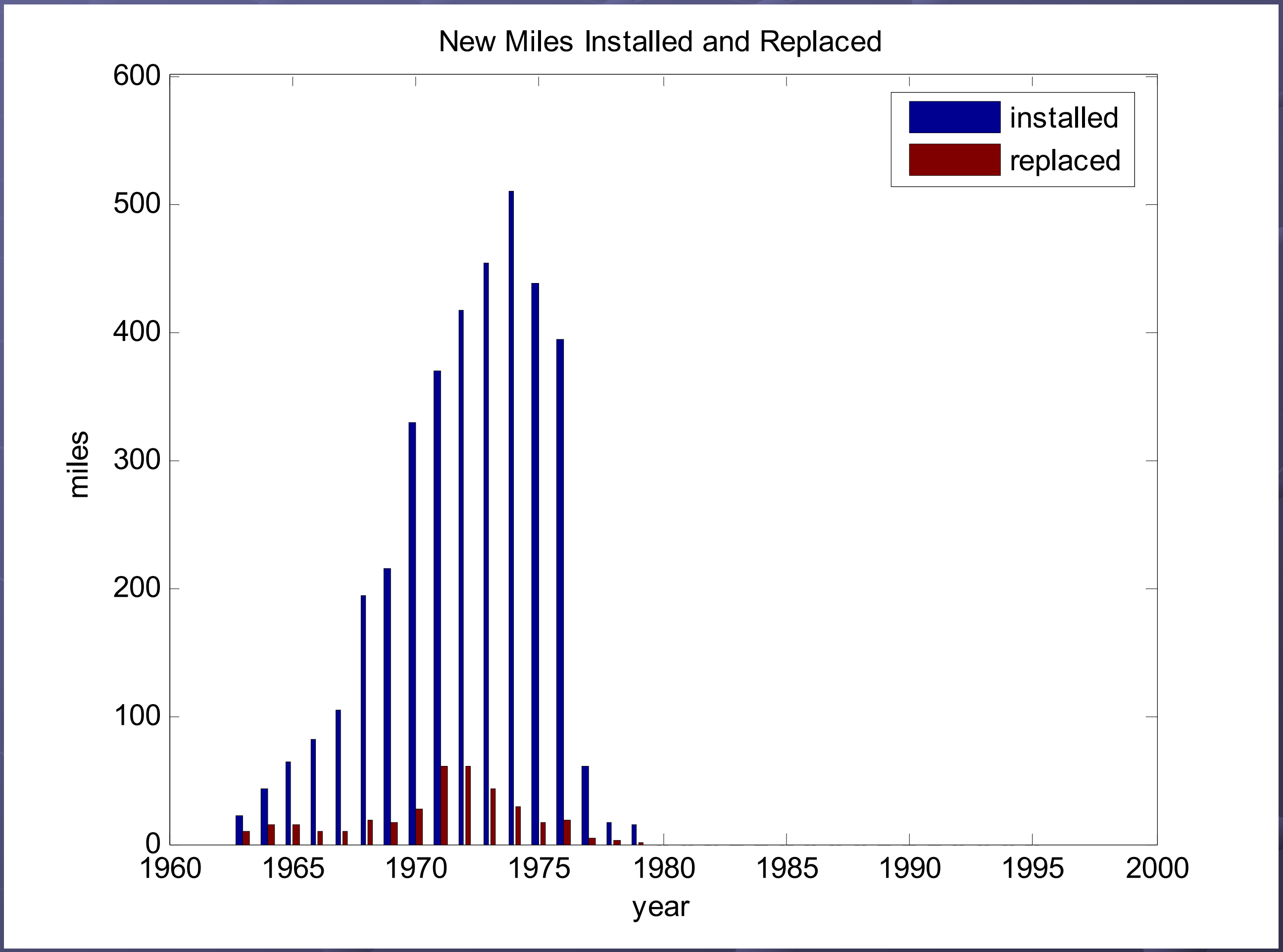
IDENTIFICATION OF {g,b,K} STATISTICAL PARAMETERS

CALCULATION OF ESTIMATED FAILURES USING {g,b,K}

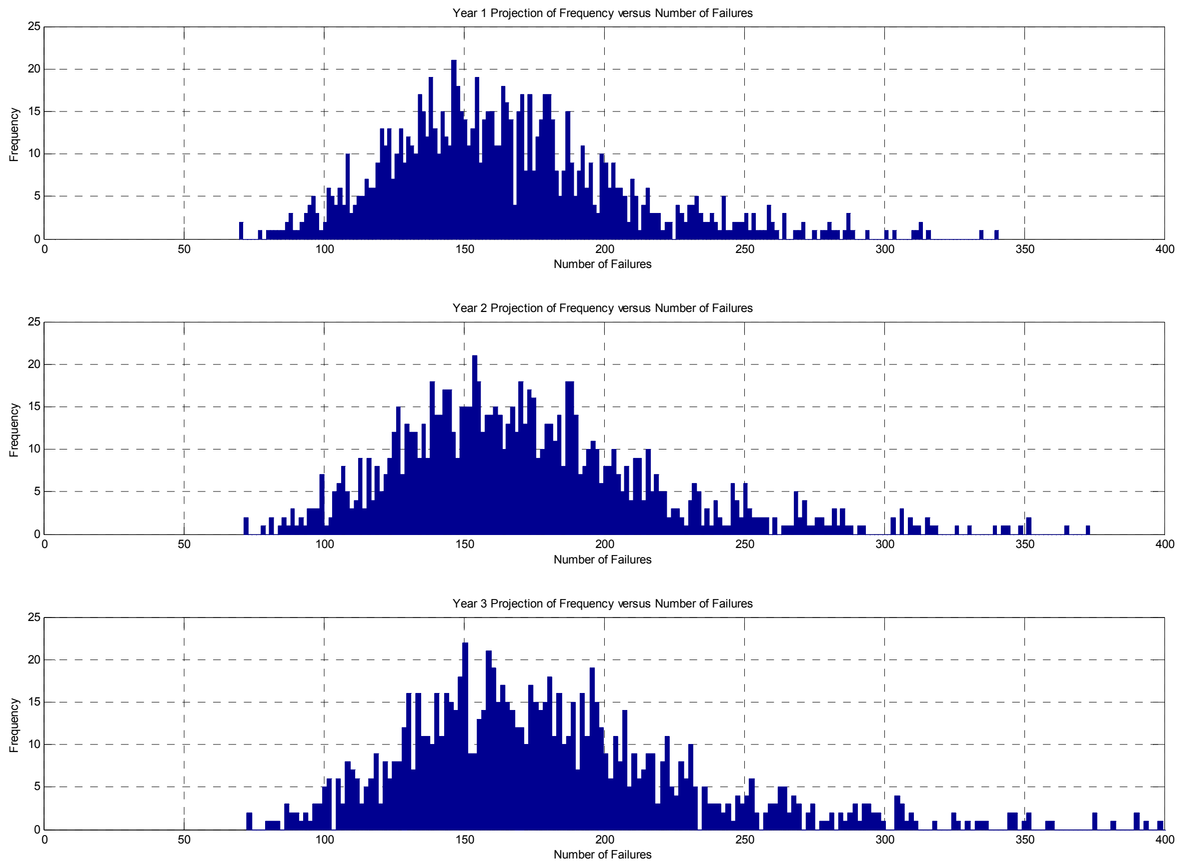
Failure Estimation



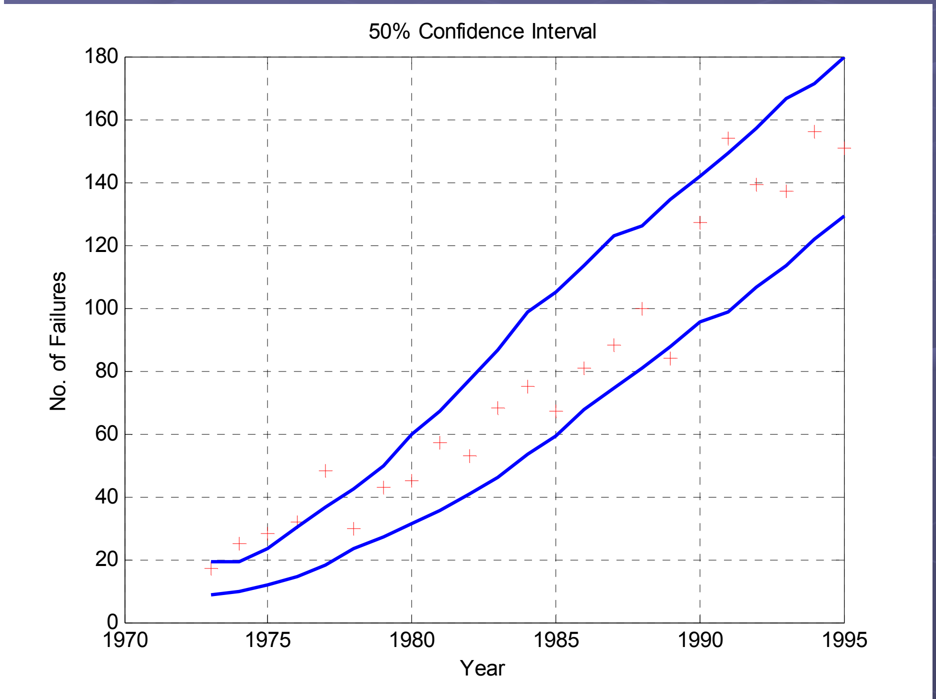
Test Data Set: New Installation and Replacement

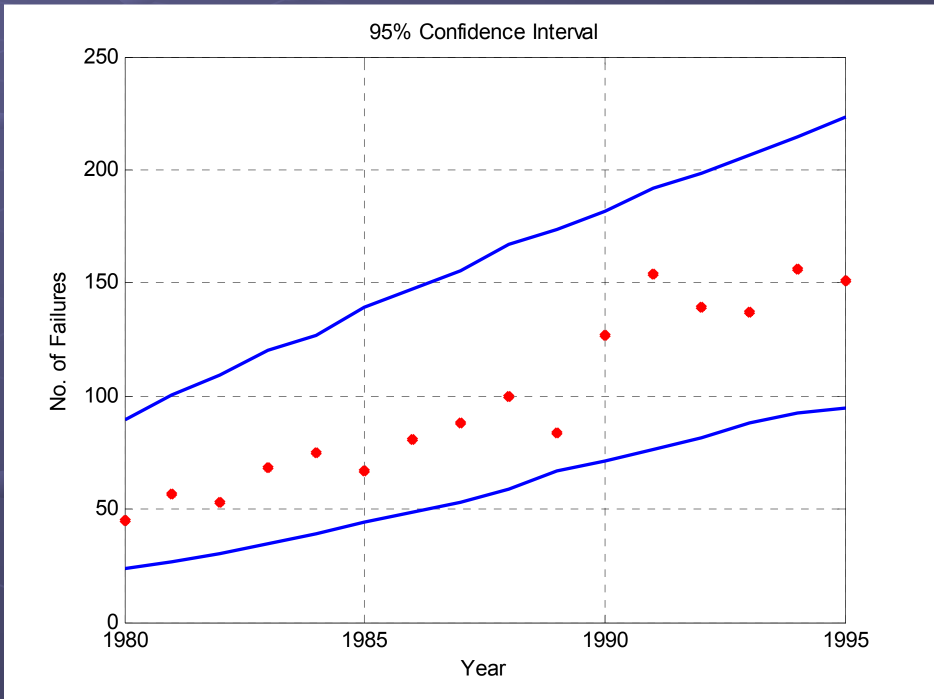


Distribution of Estimated Failures



Failure Estimation and Confidence Intervals

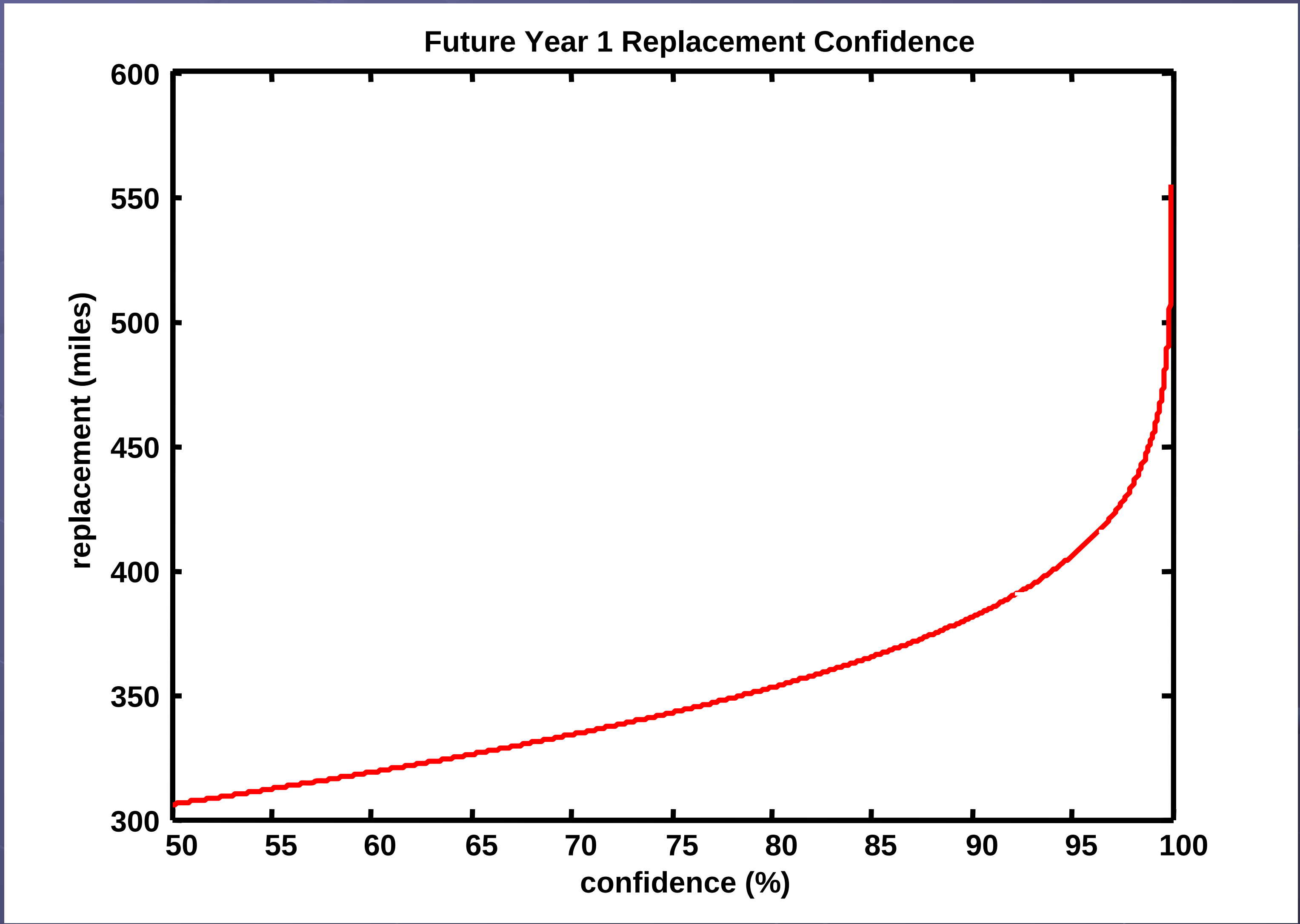




25% Confidence Interval.

95% confidence interval .

Bottom Line: 1-Year Replacement Upper Bound

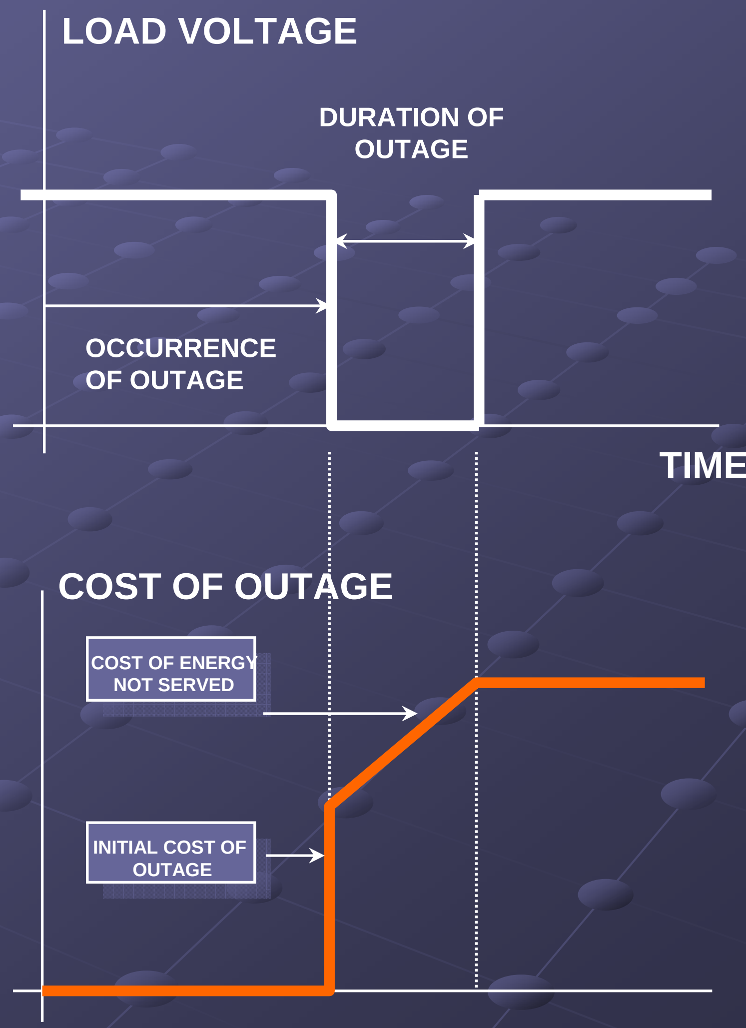


Asset Management

Source: Joshua Perkel, NEETRAC

Cost Analysis

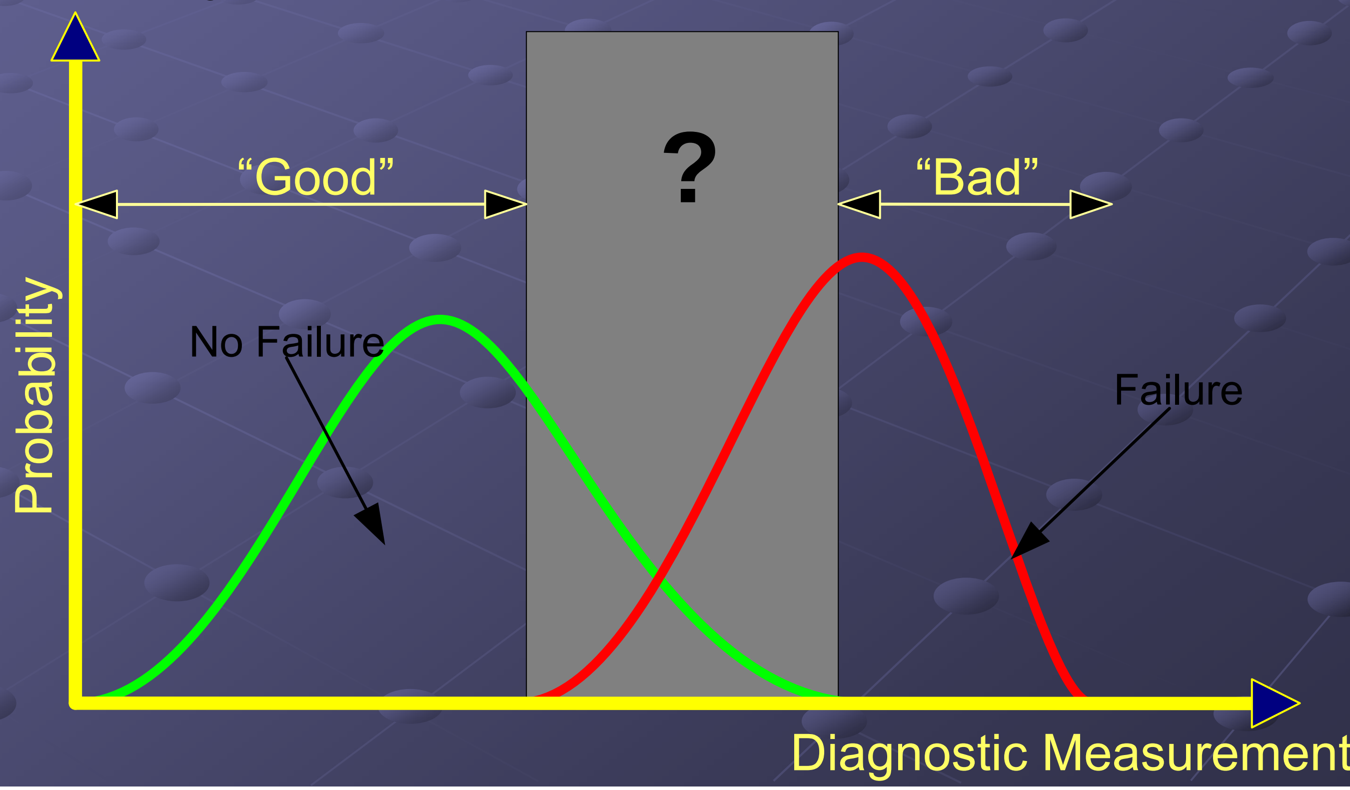
- Refurbishment
- Repair
- Preventive Replacement
- Diagnostic Testing
- Replacement on Failure
- Cost of Outage



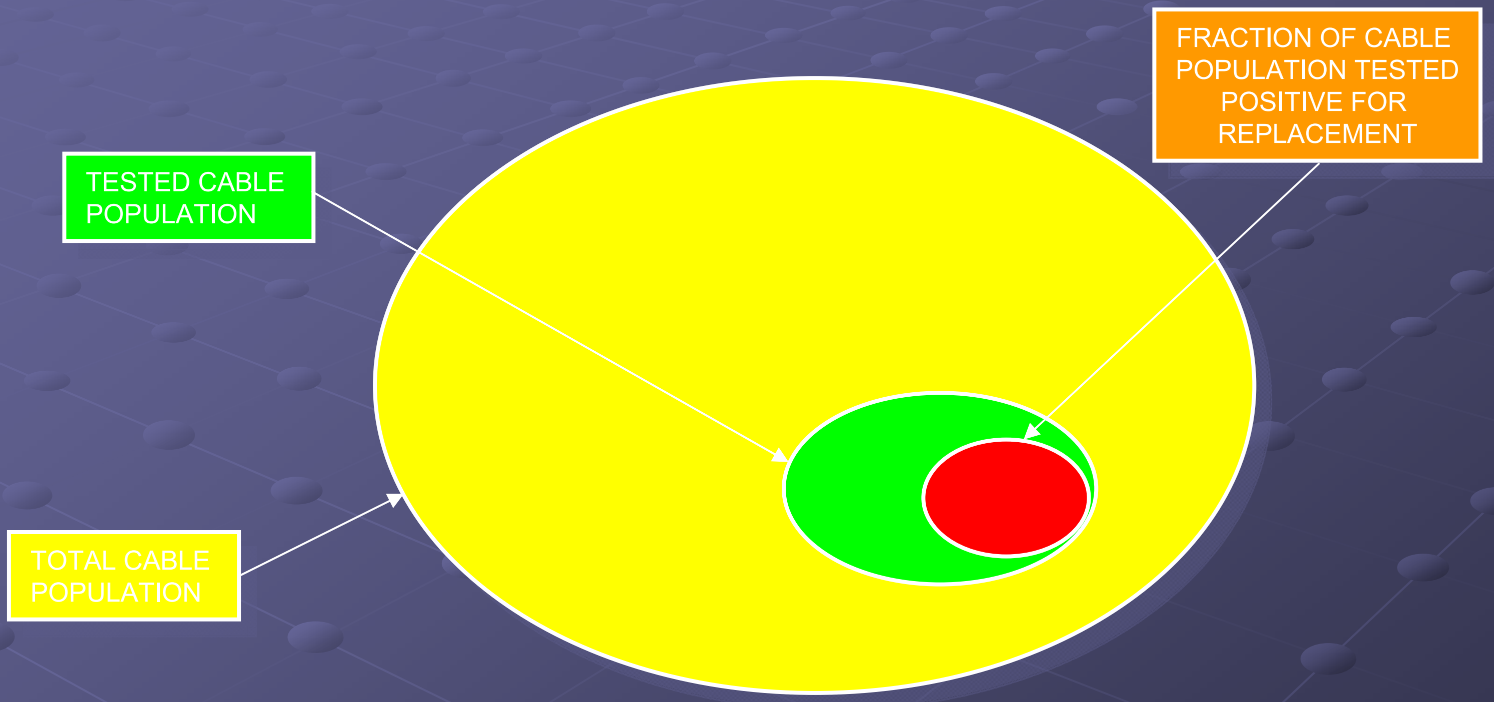
Hard to Assess the Cost of Reliability for Utilities

Motivation

- Diagnostic tests look for symptoms of degradation, not failures.
- Symptoms are difficult to relate to future failures unless they are in the extremes.



Diagnostics – where to look



Passive Approach – do nothing

Cost Parameters:

- A = Failure rates [failures/miles/year]
- B = Average length of segment [ft]
- C = Average cost of replacement cable [$/ft]
- D = Average cost of repair [$/ft]
- E = Length of population [miles]
- F = Average Momentary Cost of Outage [$/failure]
- G = Average Cost of Energy Not Served [$/min/failure]
- T_F = Average Duration of Outage [min]

$$Cost = A \cdot E \cdot \left[(C + D) \cdot B + F + G \cdot T_F \right] \quad [\$/yr]$$

Passive Cost

AVOIDABLE COST

$$Cost = A \cdot E \cdot [(C + D) \cdot B + F + G \cdot T_F] \quad [\$ / yr]$$

TOTAL NUMBER OF FAILURES PER YEAR

COST OF REPLACEMENT (CABLE + WORK)

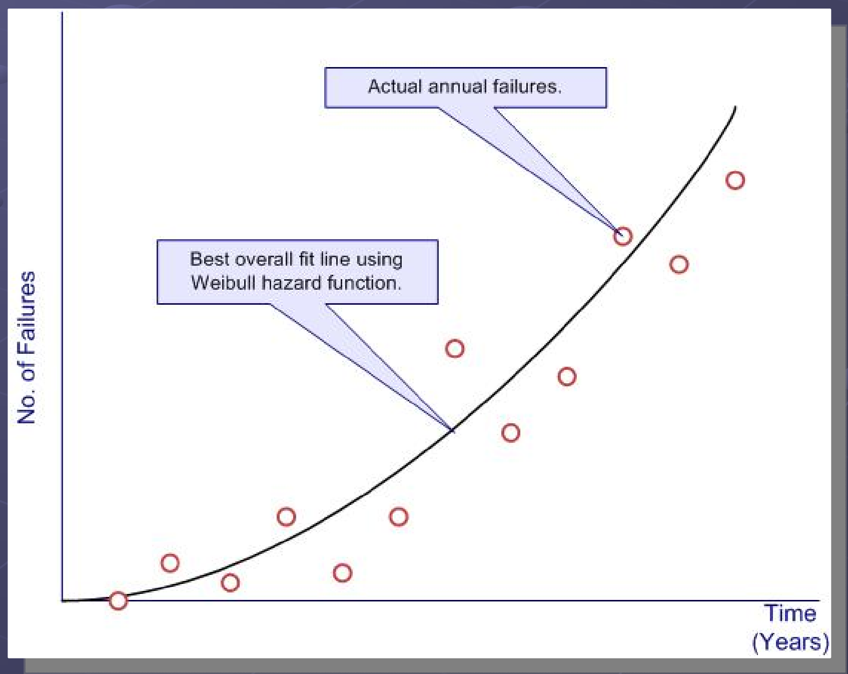
AVERAGE COST OF MOMENTARY INTERRUPTION

AVERAGE COST OF ENERGY NOT SERVED PER FAILURE

SoE1

Failure Management

- Avoidable cost can be reduced by replacing suspect cable segments in an efficient way before they fail



- Need to know how many failures are anticipated – failure forecasting

- Need to know
  - which segments to replace
  - how accurate the identification

Slide 21

SoE1 Figure Hard to read
School of ECE, 1/29/2007

Failure Management

- Cost Parameters:

  B = Average length of segment [ft]

  C = Average cost of replacement [$/ft]

  D = Average cost of repair [$/ft]

  I = Total number of tested segments [ ]

  J = Cost of diagnostic test per day [$/day]

  K = Number of segments tested per day [day^{-1}]

  ξ = Fraction of the tested segments to be replaced – ratio red to green areas

$$Cost = (C + D) \cdot B \cdot \xi \cdot I + I \cdot J / K \quad [\$ / yr]$$

Cost of Failure Management

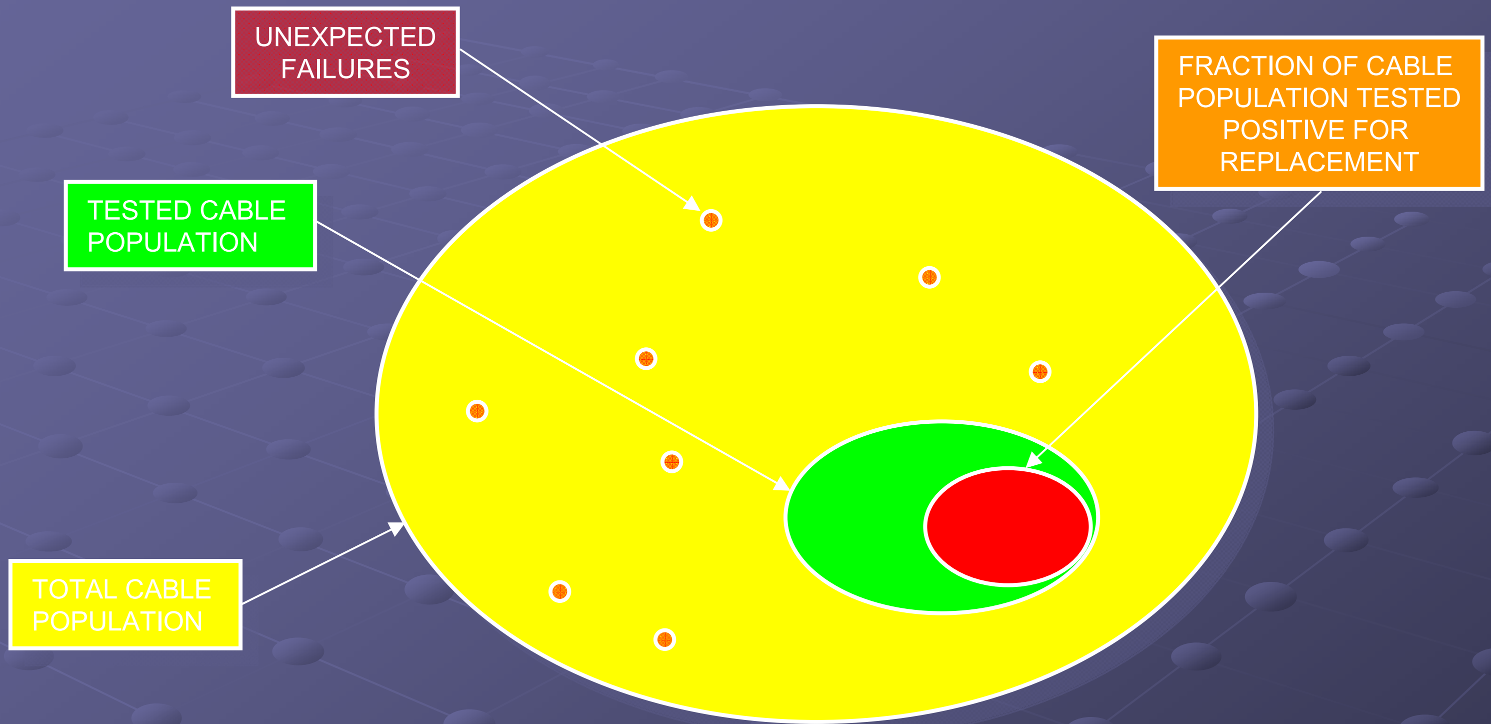
$$Cost = (C + D) \cdot B \cdot \xi \cdot I + I \cdot J / K \quad [\$ / yr]$$

- COST OF CABLE (REPLACEMENT AND WORK) PER SEGMENT
- NUMBER OF SEGMENTS NEEDING REPLACEMENT
- TOTAL NUMBER OF TESTED SEGMENTS
- COST OF DIAGNOSTIC TEST PER SEGMENT

Observations

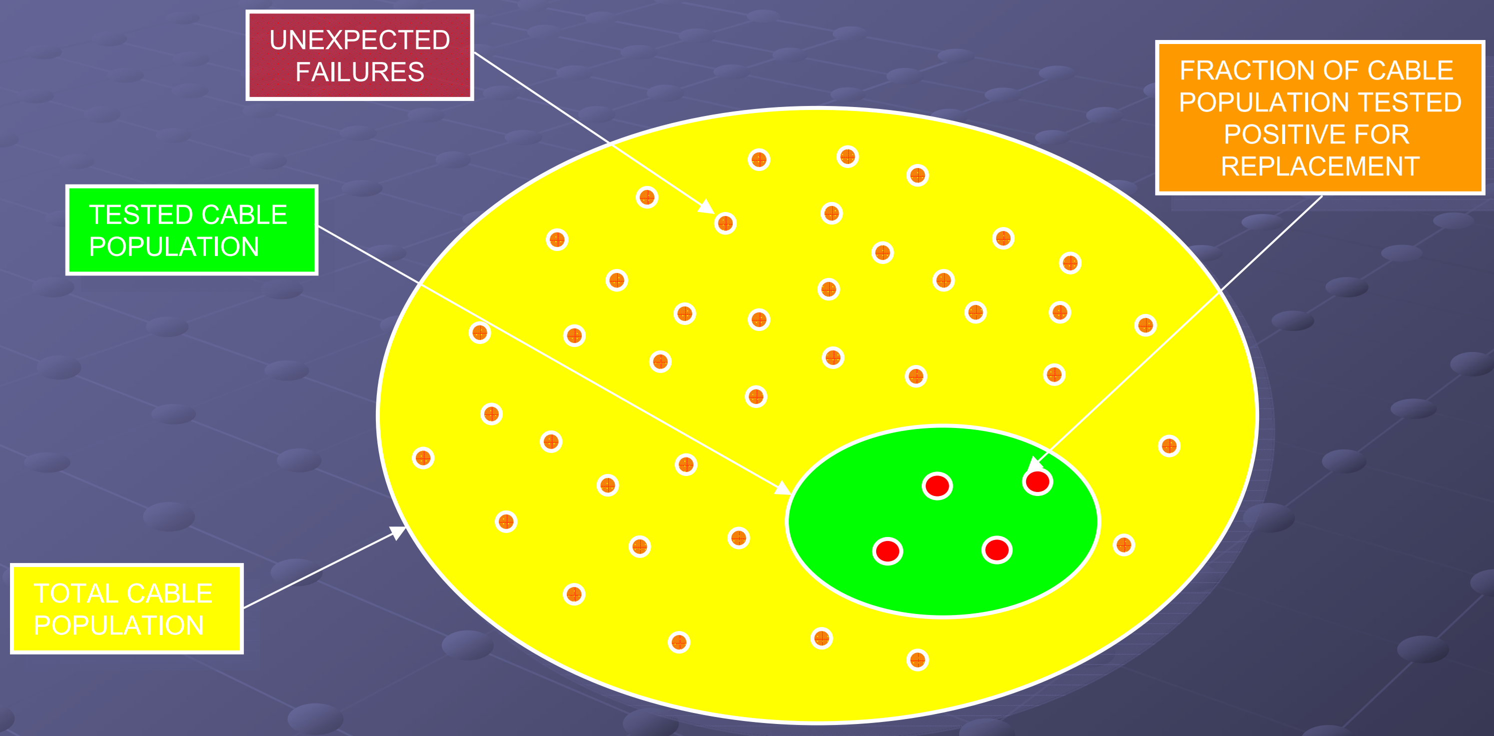
- Savings are achieved from small ξ values (only segments correctly diagnosed as bad are replaced)
- Diagnostic tests add to the cost
- It is not practical to test every segment every year (cost would be too high)
- How to determine which segments to test?

Diagnostics: Issues



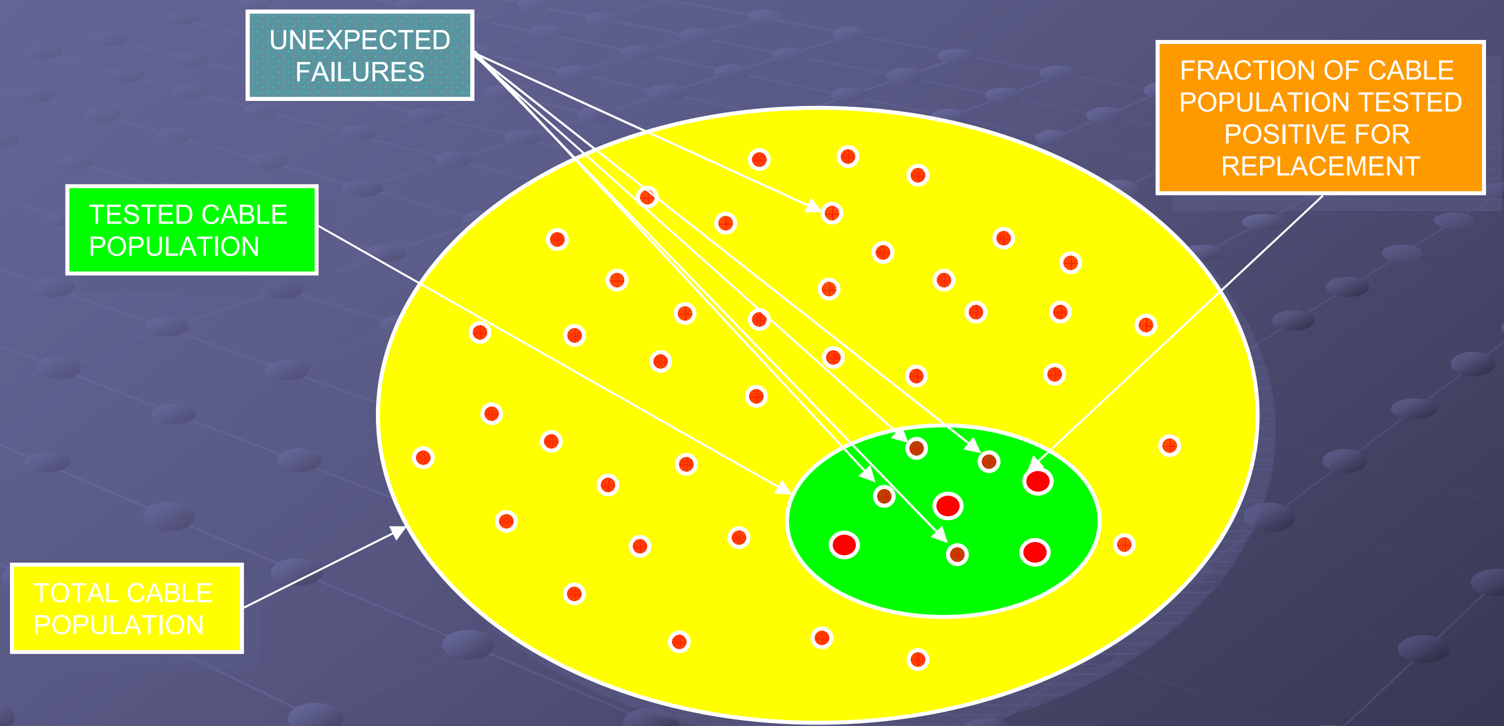
- If number of replaced segments is smaller than failure forecast, unexpected failures will likely occur
- Even if the number of replaced segments is equal to the failure forecast, there may (and probably will) be unexpected failures in the untested population

Diagnostics: Issues (2)



- If population to be tested is poorly chosen, the benefits of the diagnostic test are lost

Diagnostic Accuracy



$$P(T<0|G)=1-\varepsilon \qquad P(T>0|G)=\varepsilon$$

$$P(T>0|B)=1-\varepsilon \qquad P(T<0|B)=\varepsilon$$

Diagnostic Accuracy (2)

$$P(G|T<0)=\frac{P(T<0|G)P(G)}{P(T<0|G)P(G)+P(T<0|B)P(B)}=$$

$$=\frac{1\cdot P(G)}{1\cdot P(G)+0\cdot P(B)}=\frac{P(G)}{P(G)}=1$$

If diagnostic accuracy is perfect, testing will identify all the good (G) and bad (B) tested components

Diagnostic Accuracy (3)

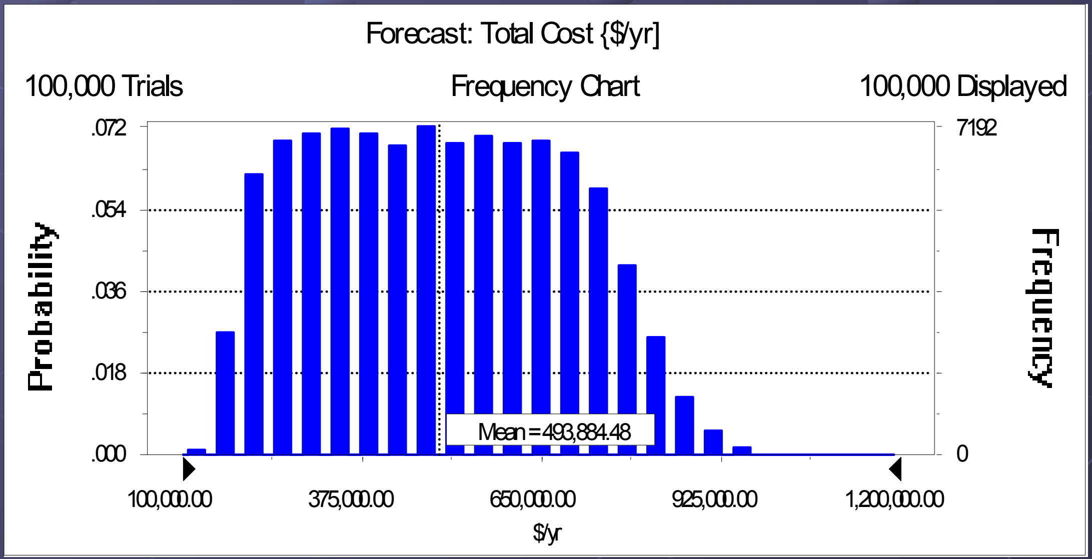
$$P(G|T<0) = \frac{P(T<0|G)P(G)}{P(T<0|G)P(G) + P(T<0|B)P(B)} =$$

$$= \frac{0.5 \cdot P(G)}{0.5 \cdot P(G) + 0.5 \cdot P(B)} = \frac{0.5 \cdot P(G)}{0.5} = P(G)$$

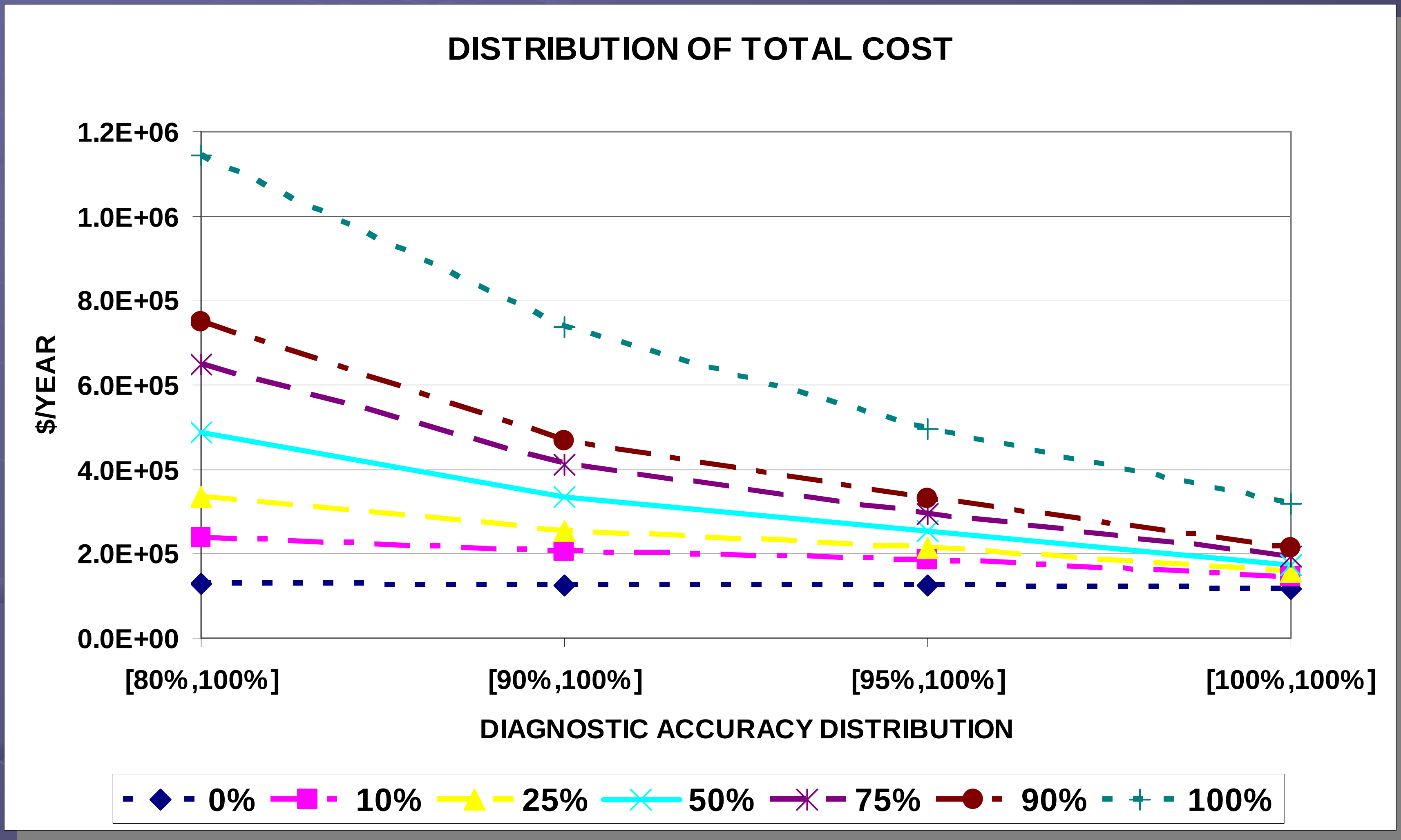
If diagnostic accuracy is bad, testing will identify all the good (G) and bad (B) tested components only as their proportions in the tested population

Replacement Cost

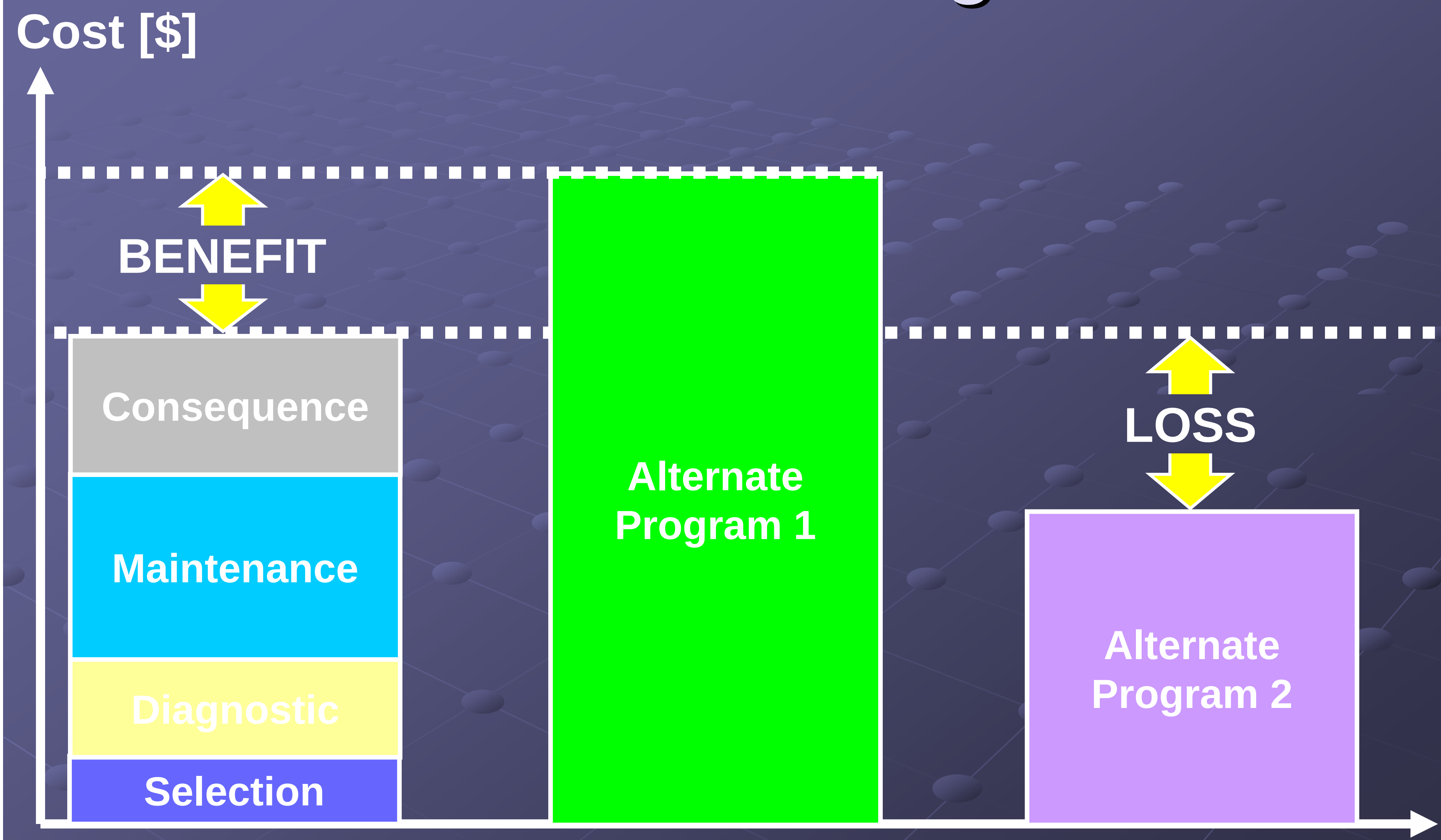
- Population: *100 miles*
- Diagnostic Cost: *$6k/mile*
- Cycle: *6 years*
- Cost per annum: *$100k/yr*
- Failure rate: *30 failures/100 mi/yr*
- Replacement on failure: *uniformly distributed [$5k, $10k]*
- Replacement on failure: *uniformly distributed [$5k, $10k]*
- Cable cost: *uniformly distributed between [$27,$33]*
- Diagnostic accuracy: *uniformly distributed in [80%,100%]*



Replacement Cost



Cost Benefit of Diagnostics



Source: Joshua Perkel, NEETRAC

Conclusions

- **Failure Forecasting algorithm provides some guidance under the assumption that oldest population of equipment is the most prone to failures**
- **Diagnostic testing may provide better targeting of the candidates for replacement, but at a cost (both due to the procedure and its limited accuracy)**
- **Analysis of different scenarios of desired failure performance assist in formulating optimal strategies**
- **Circumstances may significantly influence the cost of diagnostic testing**