Accelerated Testing and Preventive Maintenance in Acquisition, Maintenance and Operation of Vehicle Systems using Time-Dependent Reliability / Durability Principles

Amandeep Singh[1], Igor Baseski[1,2]
[1]U.S. Army, RDECOM TARDEC;
[2]Ph.D. Student, Oakland University

Zissimos P. Mourelatos, Jing Li
Mechanical Engineering Department
Oakland University
Rochester, MI 48309, USA

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
24 MAY 2011	**Briefing Charts**	**24-05-2011 to 24-05-2011**

4. TITLE AND SUBTITLE
ACCELERATED TESTING AND PREVENTIVE MAINTENANCE IN ACQUISITION, MAINTENANCE AND OPERATION OF VEHICLE SYSTEMS USING TIME-DEPENDENT RELIABILITY/DURABILITY PRINCIPLES

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Amandeep Singh; Igor Baseski; Zissimos Mourelatos; Jing Li

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Oakland University,Mechanical Engineering Department,Rochester,MI,48309

8. PERFORMING ORGANIZATION REPORT NUMBER
; #22500

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 E.11 Mile Rd, Warren, MI, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#22500

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Automotive Research Center (ARC) Conference briefing

14. ABSTRACT
N/A

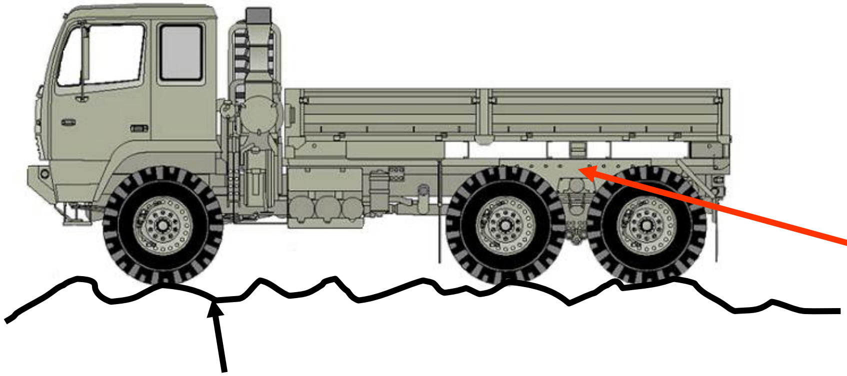
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**38**	

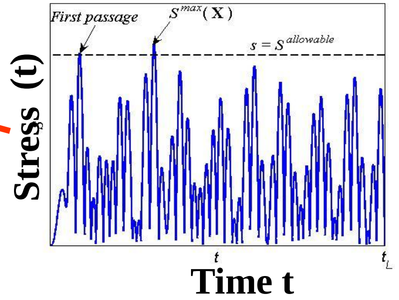
Army Needs in Reliability, Maintenance and Logistics

- Reduce operations and maintenance costs
- Increase effectiveness of fleet logistics
- Control lifecycle cost and also use it in design and procurement
- Improve availability; schedule maintenance
- Use both analytical and experimental / field data to estimate reliability

Background



Random Process
(Field)



Input
Random
Process

Vehicle

Output
Random
Process

Random Process leads to Time-Dependent Reliability

Research Statement

Develop methodologies to obtain a preventive maintenance schedule and to assess and improve the reliability / durability of vehicle systems using

- **Experimental (field) data**
- **“Expert” opinion**

Previously and currently at TARDEC

- **Predictive tools (physics-of-failure data)**

Current research

Overview

Part 1:

Optimal preventive maintenance schedule using time-dependent reliability and lifecycle cost

Part 2:

Accelerated testing method based on importance sampling using few tests which run for only a short time

Part 1: Optimal Preventive Maintenance Schedule

What is Reliability? Cumulative Probability of Failure

Reliability at time t is the probability that the system has not failed before time t.

$$F_T^c(t_L) = P\left(\exists t \in [0, t_L], such \quad that \quad g(\mathbf{X}(t), t) \leq 0\right)$$

Cumulative Prob. of Failure

$$F_T^i(t_L) = P\left(g(\mathbf{X}(t_L), t_L) \leq 0\right)$$

Instantaneous Prob. of Failure

Calculation Methods for $F_T^c(t)$

- **Maximum Response Method**
- **Niching GA & Lazy Learning Local Metamodeling**

$\Big\}$ **Analytical**

- **MCS / Importance sampling**

$$F_T^c(t) = 1 - \exp[-\int_0^t \lambda(t) dt]$$

$\Big\}$ **Simulation-based**

Definition of Lifecycle Cost

Lifecycle Cost = Production Cost

+ Inspection Cost

+ Expected Variable Cost

Quality

Time-Dependent System Reliability

Definition of Lifecycle Cost

$$C_L\left(\mathbf{d},\mathbf{X},t_f,r\right)=C_P\left(\mathbf{d},\mathbf{X}\right)+C_I\left(\mathbf{d},\mathbf{X},t_0\right)+C_V^E\left(\mathbf{d},\mathbf{X},t_f,r\right)$$

Lifecycle Cost

Production Cost

Inspection Cost

Expected Variable Cost

Final time

Interest rate

$$C_V^E\left(\mathbf{d},\mathbf{X},t_f,r\right)=\int_0^{t_f} c_F(t)\,e^{-rt} f_T^c(t)\,dt$$

Cost of failure at time t

PDF of time to failure time

$$F_T^c\left(t_L\right)=P\left(\exists t\in\left[0,t_L\right], such \quad that \quad g\left(\mathbf{X}(t),t\right)\le 0\right)$$

Estimation of Time for Preventive Maintenance

$$\max_{\mathbf{d},\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t_M} \quad t_M$$

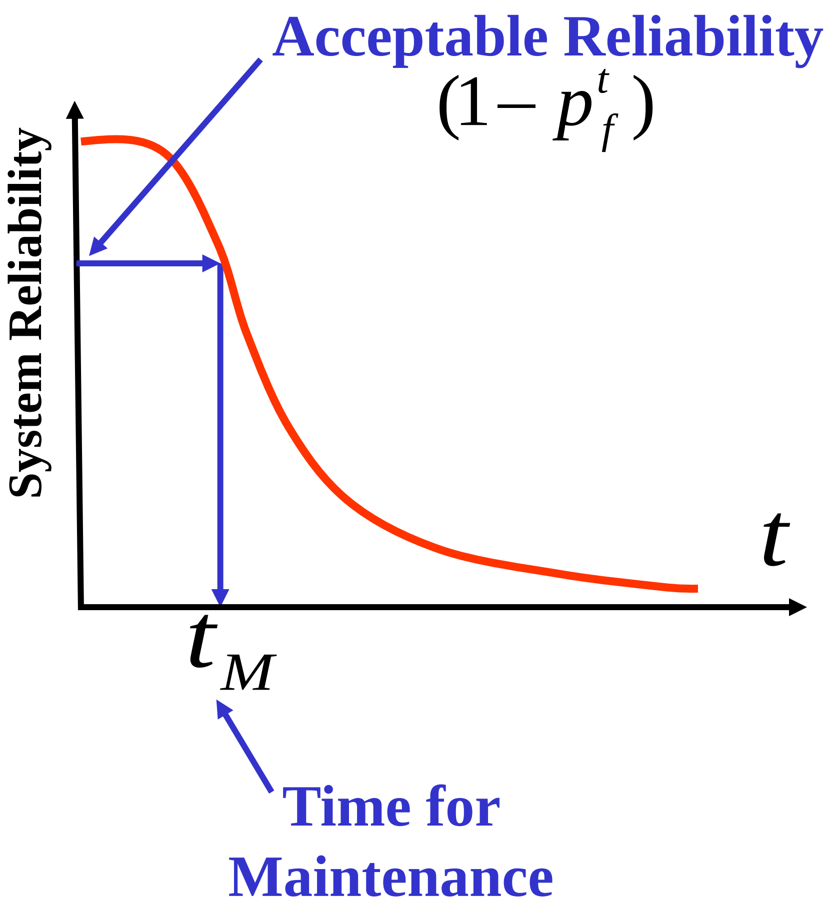
s. t. $$C_L\left(\mathbf{d},\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t_M,r\right)\le C_L^t$$

$$F_T^c\left(\mathbf{d},\mathbf{X},t_M\right)\le 1-R^t\left(t_M\right)$$

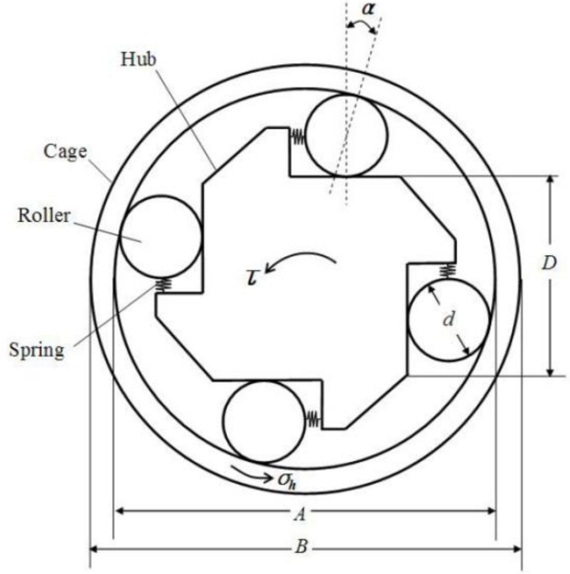
$$\mathbf{d}_L\le\mathbf{d}\le\mathbf{d}_U$$

$$\boldsymbol{\mu}_{\mathbf{X}_L}\le\boldsymbol{\mu}_{\mathbf{X}}\le\boldsymbol{\mu}_{\mathbf{X}_U}$$

$$\boldsymbol{\sigma}_{\mathbf{X}_L}\le\boldsymbol{\sigma}_{\mathbf{X}}\le\boldsymbol{\sigma}_{\mathbf{X}_U}$$



A Roller Clutch Example



Random Variables: D, d, A

Due to degradation:

$$\mathbf{D} \rightarrow \mathbf{D}(1-kt)$$

$$\mathbf{d} \rightarrow \mathbf{d}(1-kt)$$

$$\mathbf{A} \rightarrow \mathbf{A}(1+kt)$$

with: $k = 2.5E-04 \quad mm/year$

Constraints:

- **Contact angle** $\alpha = 0.11 \pm 0.06 \quad \text{rad}$
- **Torque** $\tau >= 3000 \quad \text{Nm}$
- **Hoop stress** $\sigma_h \leq 400 \quad MPa$

$$g_1(D,d,A) = 0.05 - \cos^{-1}\left(\frac{D-d}{A-d}\right) \leq 0$$

$$g_2(D,d,A) = \cos^{-1}\left(\frac{D-d}{A-d}\right) - 0.17 \leq 0$$

$$g_3(D,d,A) = 3000 - NL\left(\frac{\sigma_c}{c_1}\right)^2 \frac{D^2 d}{4(D+d)} \sqrt{1-S^2} \leq 0$$

$$g_4(D,d,A) = \frac{N}{2\pi}\left(\frac{\sigma_c}{c_1}\right)^2 \left(\frac{Dd}{(D+d)}\right) \frac{S}{A}\left(\frac{B^2+A^2}{B^2-A^2}\right) - 400E06 \leq 0$$

Roller Clutch: Lifecycle Cost

$$\boxed{C_L = C_P + C_I + C_V^E}$$

where:

$$C_P = \left(3.5 + \frac{0.75}{3\sigma_D}\right) + \left(3.0 + \frac{0.65}{3\sigma_d}\right) + \left(0.5 + \frac{0.88}{3\sigma_A}\right)$$

$$C_I = 20F_T^i(\mathbf{X}, t_0) \qquad C_V^E = \int_0^{t_f} 20e^{-rt} f_T^c(t)\,dt$$

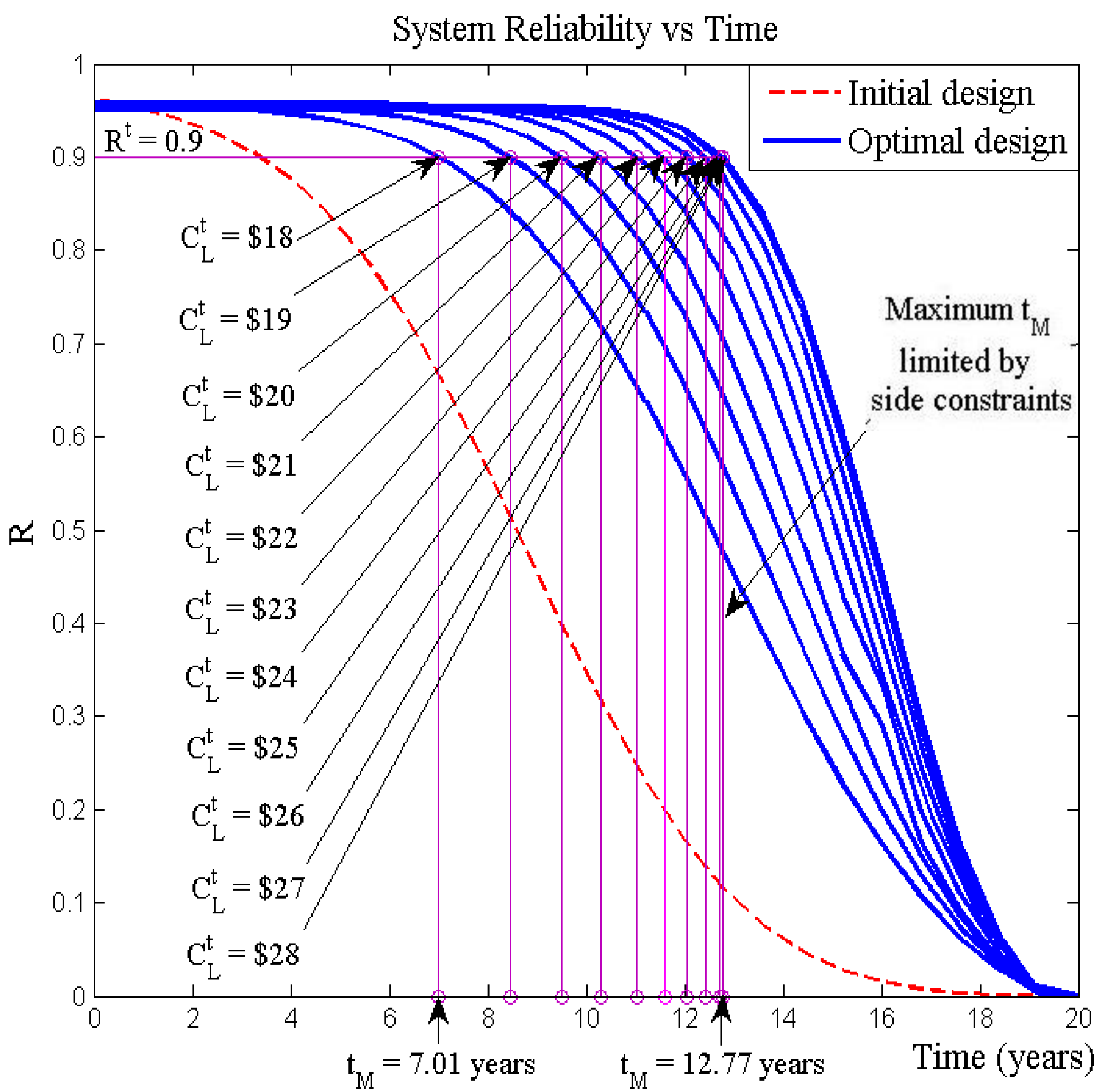
Scrap cost/unit

$t_f = 10 \quad years$

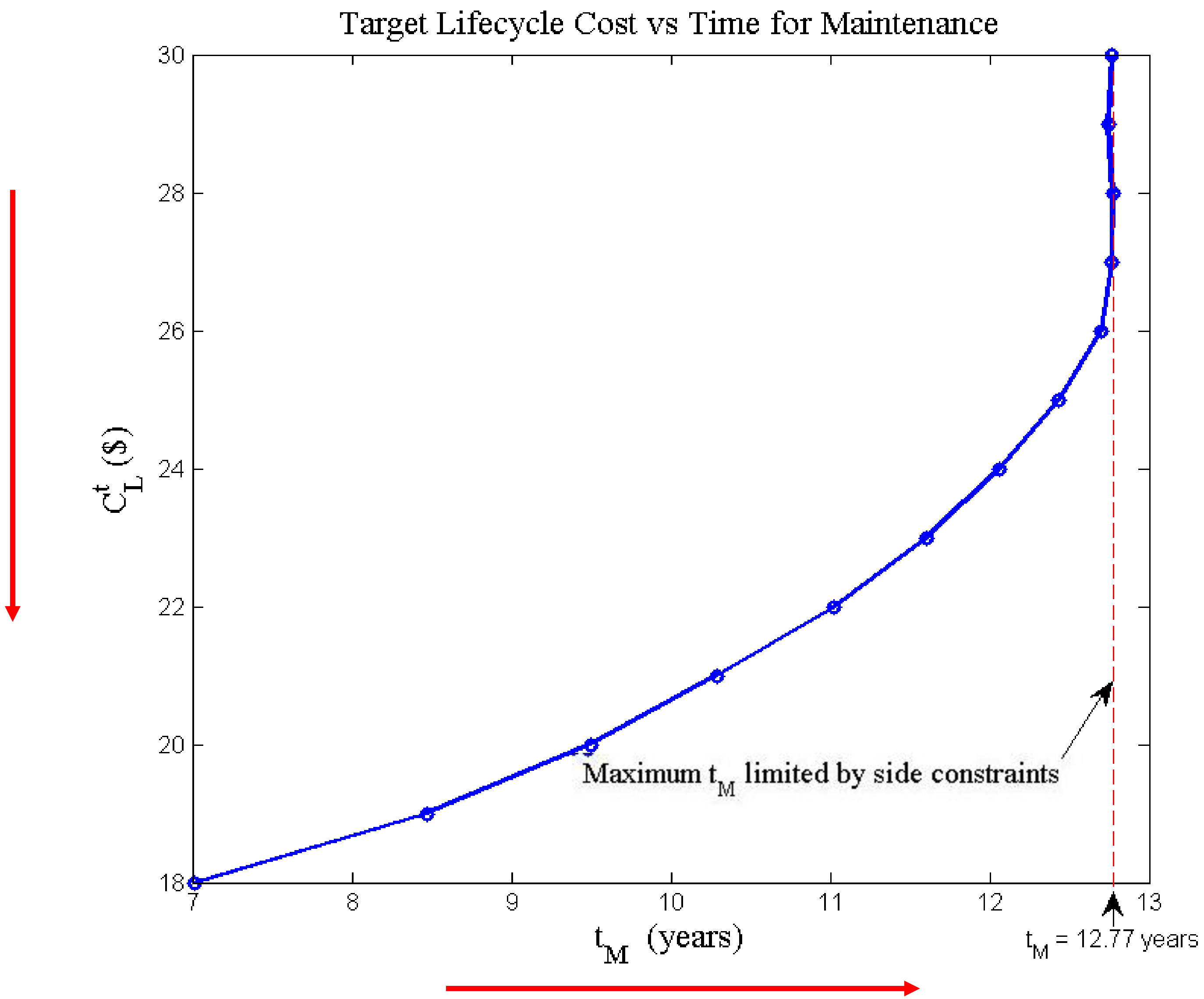
$r = 3\%$

Failure cost/unit (warranty cost)

Roller Clutch: Reliability vs Time-to-Maintenance



Roller Clutch: Pareto Optimality between Time-to-Maintenance and Cost



UNCLASSIFIED

Roller Clutch: Pareto Optimality between Time-to-Maintenance and Cost

Design Variables:

$$\boldsymbol{\mu}_{\mathbf{X}} = \{\mu_D, \mu_d, \mu_A\} \qquad \sigma_{\mathbf{X}} = \{\sigma_D, \sigma_d, \sigma_A\}$$

Side Constraints:

$$55.0973 \le \mu_D \le 55.4973 \qquad 22.66 \le \mu_D \le 23.06 \qquad 101.49 \le \mu_A \le 101.89$$

$$0.04 \le \sigma_D \le 0.08 \qquad 0.03 \le \sigma_d \le 0.1 \qquad 0.07 \le \sigma_A \le 0.113$$

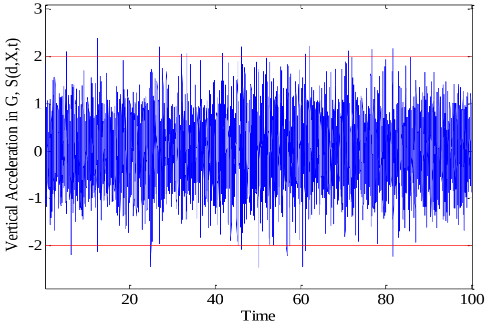
c_L^t	18	19	20	21	22	23	24	25	26	27	28
μ_D	55.4946	55.4973	55.4973	55.3822	**55.4973**	**55.4973**	**55.4973**	**55.4973**	**55.4973**	**55.4973**	**55.4973**
μ_d	22.7562	22.7735	22.7867	22.8535	22.8071	22.8146	22.8208	22.8259	22.8296	22.8315	22.8316
μ_A	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**	**101.49**
σ_D	**0.08**	**0.08**	0.0771	0.0693	0.0661	0.0593	0.054	0.0496	0.0423	**0.04**	**0.04**
σ_d	0.0639	0.0543	0.0481	0.0449	0.0407	0.0368	0.0334	0.0306	**0.03**	**0.03**	**0.03**
σ_A	0.1107	0.0946	0.084	0.0763	0.0701	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**

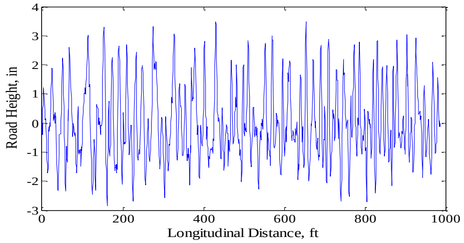
Part 2: Accelerated Testing using Importance Sampling

Problem Description

Random Variables

Vertical Accel. (G)





Terrain

Vehicle speed : 20 mph; Mission distance : 100 miles

Simulation can be practically performed for a short-duration time

Our Approach

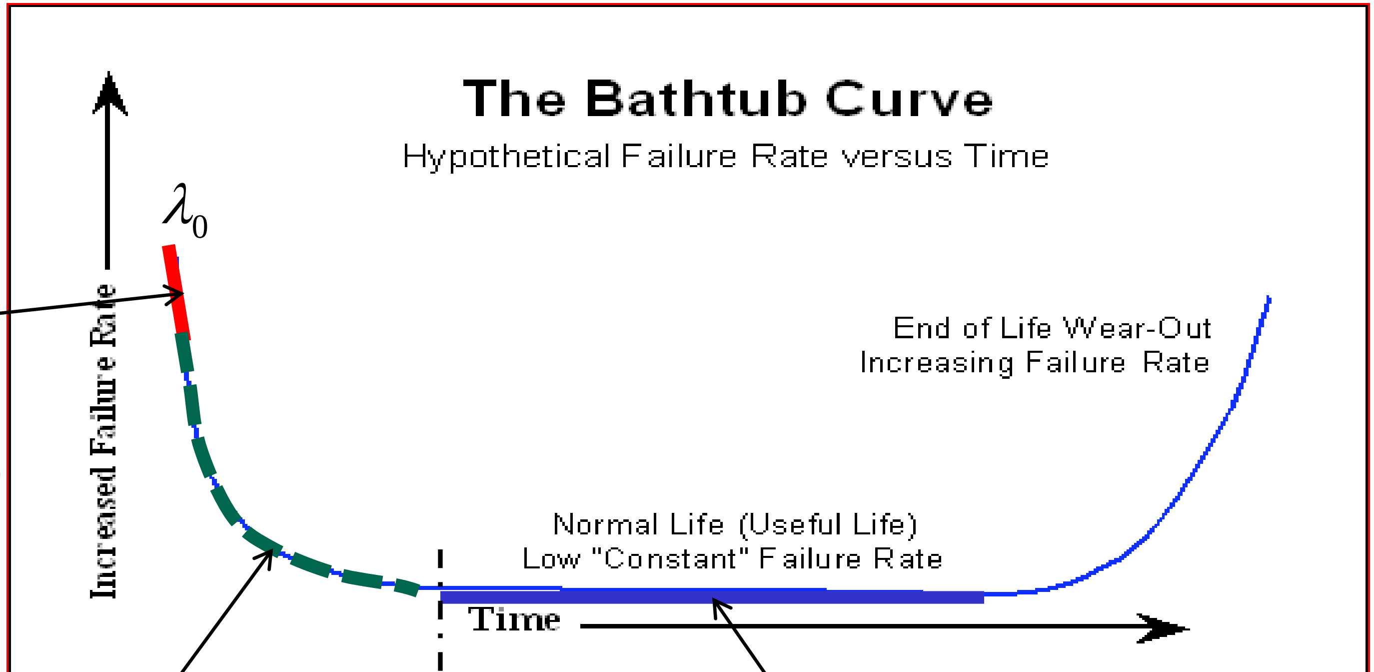
A novel MC-based method to calculate the time-dependent reliability (cumulative probability of failure) based on :

- **short-duration data and an exponential extrapolation using MCS or Importance Sampling (Infant Mortality)**
- **Poisson's assumption (Useful Life)**

Efficient MC Simulation Approach

MCS

$$b = -\frac{1}{\lambda_0}\left(\frac{d\hat{\lambda}}{dt}\right)_{t=0}$$



t_{int}

Poisson's Assumption

Exponential Extrapolation

$$\boxed{\hat{\lambda}(t) \approx \lambda_0 e^{-bt}}$$

$$F_T^c(t) = \begin{cases} 1 - e^{-\int_0^t \hat{\lambda}(t)dt} & , t \in [0, t_{\text{int}}] \\ 1 - (1 - F_T^c(t_{\text{int}}))e^{-\nu_m (t - t_{\text{int}})} & , t \in [t_{\text{int}}, t_f] \end{cases}$$

Poisson Assumption

$$\boxed{F_T^c(t_{\min}, t) = 1 - (1 - F^i(t_{\min}))e^{-m_1}}$$

where :

$$m_1 = E\left[N^+(t_{\min}, t)\right] = \int_{t_{\min}}^{t} \nu^+(t)\,dt = \nu_m\left(t - t_{\min}\right)$$

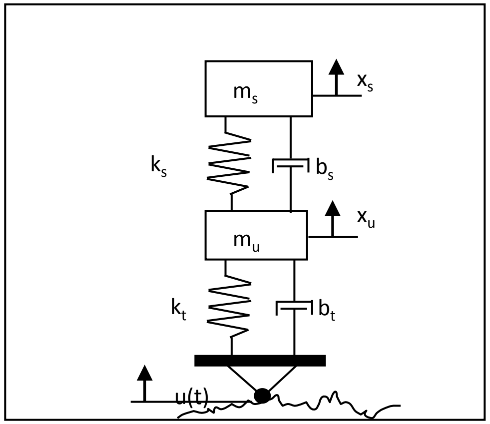
Number of out-crossings

$$\nu^+(t) = \lim_{\Delta\tau \to 0, \Delta\tau > 0} \frac{P\left[g(\mathbf{d}, \mathbf{X}, t) > 0 \cap g(\mathbf{d}, \mathbf{X}, t + \Delta\tau) \leq 0\right]}{\Delta\tau}$$

Out-crossing rate

Quarter-Car Model on Stochastic Terrain

Constant design parameters:
m_s =1000 kg
m_u =100 kg
Vehicle speed = 20 mph



Random Input variables

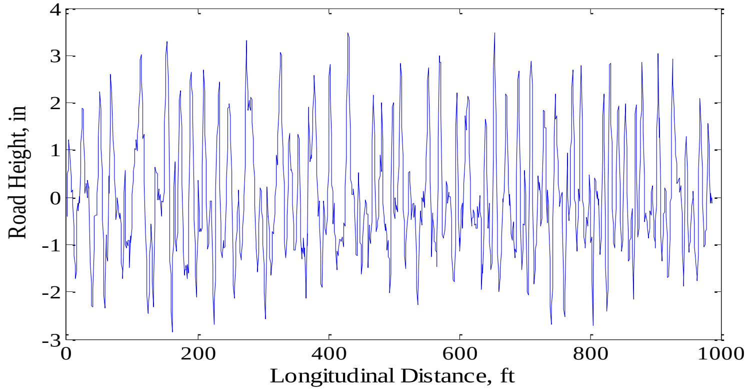
Damping, $b_s \sim N(7000, 1400^2)$

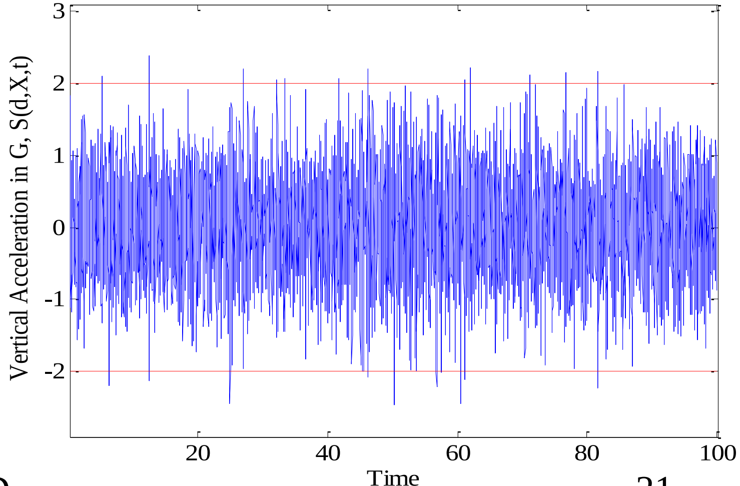
Stiffness, $k_s \sim N(40\times10^3, (4\times10^3)^2)$

Random Input Process: Experimental Stochastic Terrain from Yuma Proving Grounds.

Random Output Process
(Vertical Acceleration, G')

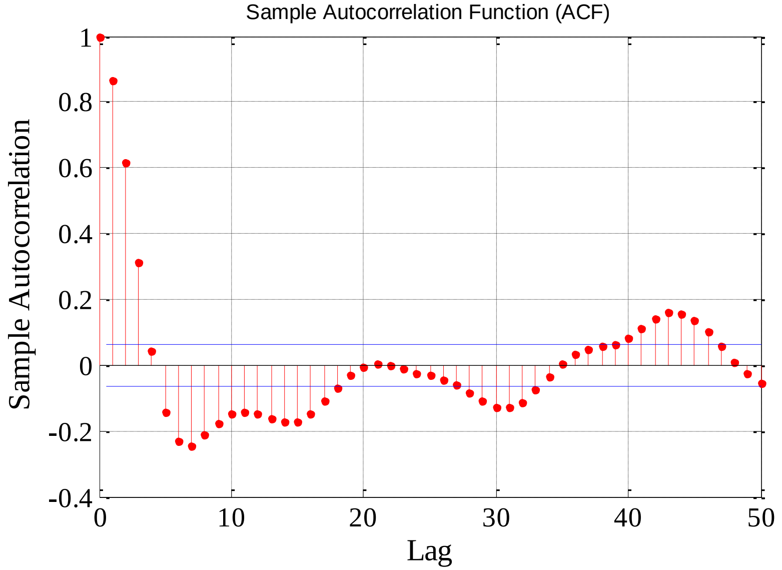
Threshold = 2G



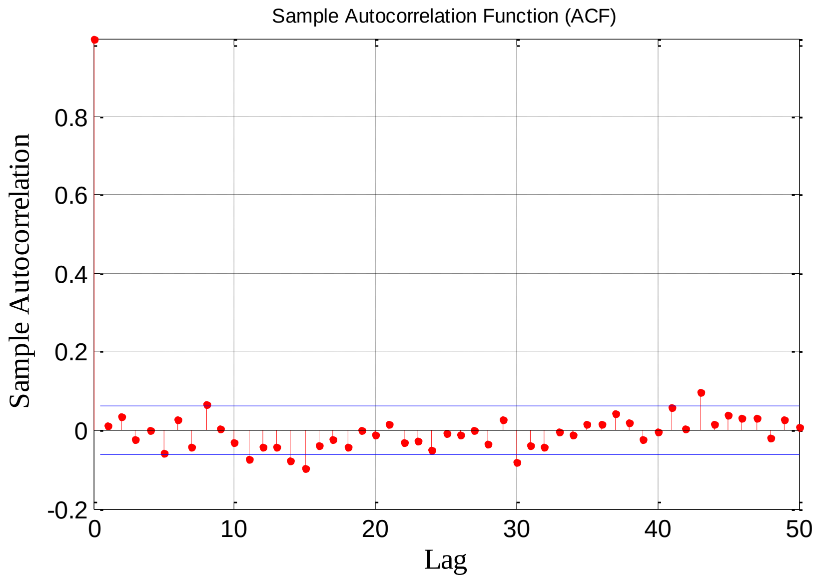


AR(3) model was identified based on:

Autocorrelation Function



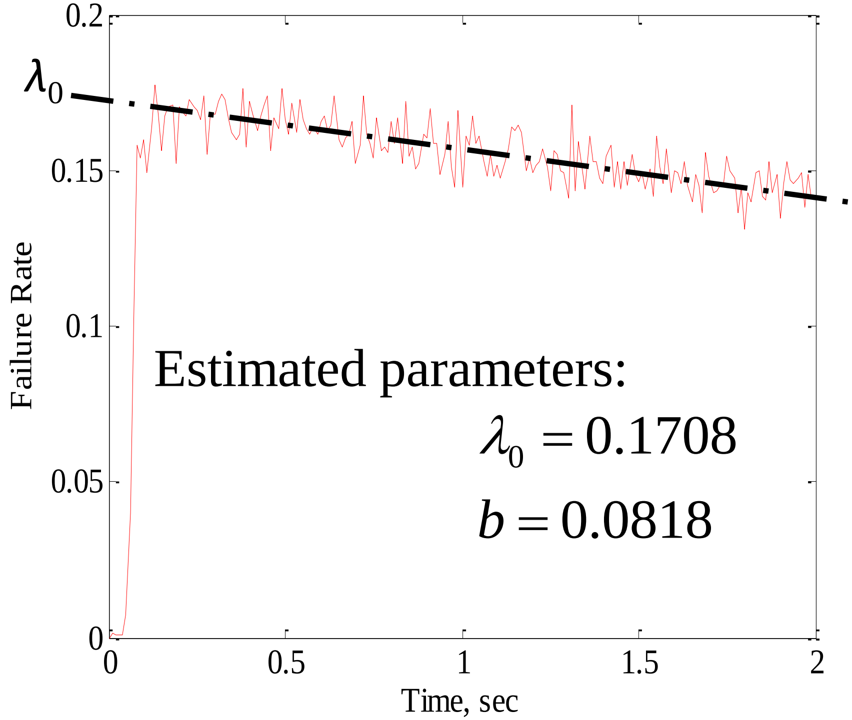
Autocorrelation of Residual process

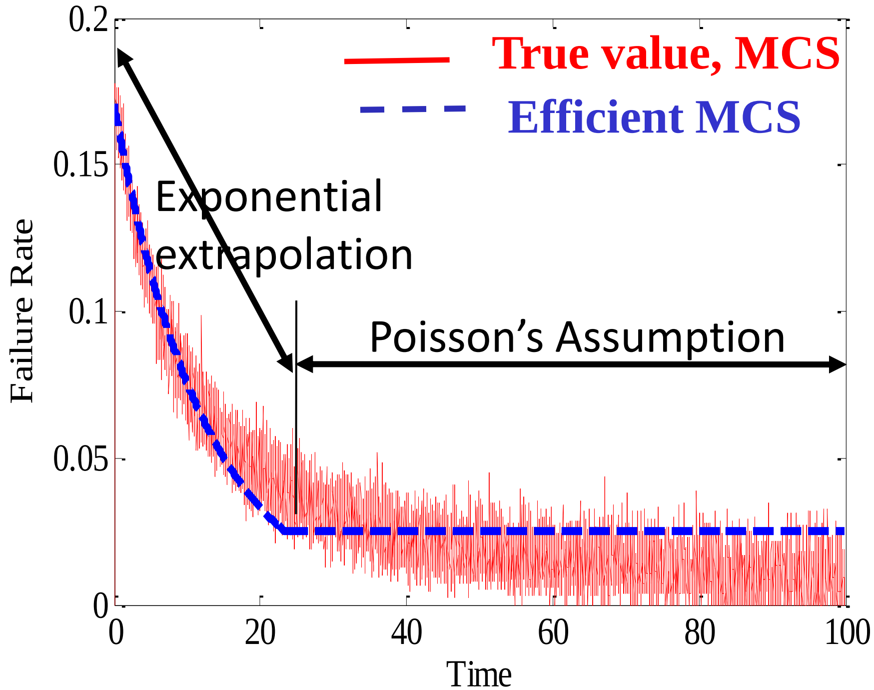


$$u_i = 1.2456 \quad u_{i-1} - 0.2976 \quad u_{i-2} - 0.1954 \quad u_{i-3} + \varepsilon_i(0, \quad 0.5132^2)$$

Statistical tests were performed to verify the model

Quarter-Car Model: Results
(Failure Rate Estimation for Threshold = 2G)





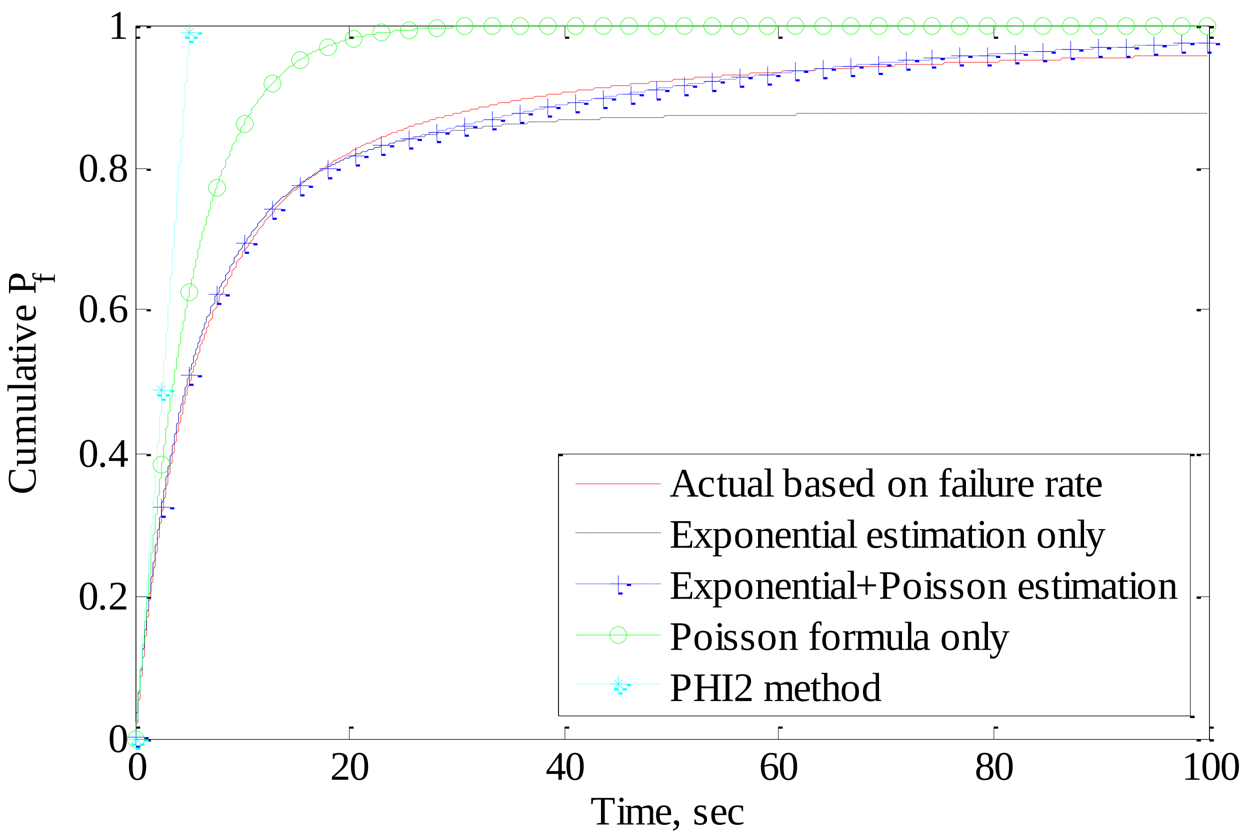
Estimation requires short duration MCS

Exponential extrapolation

$$\hat{\lambda}(t) \approx \lambda_0 e^{-bt}$$

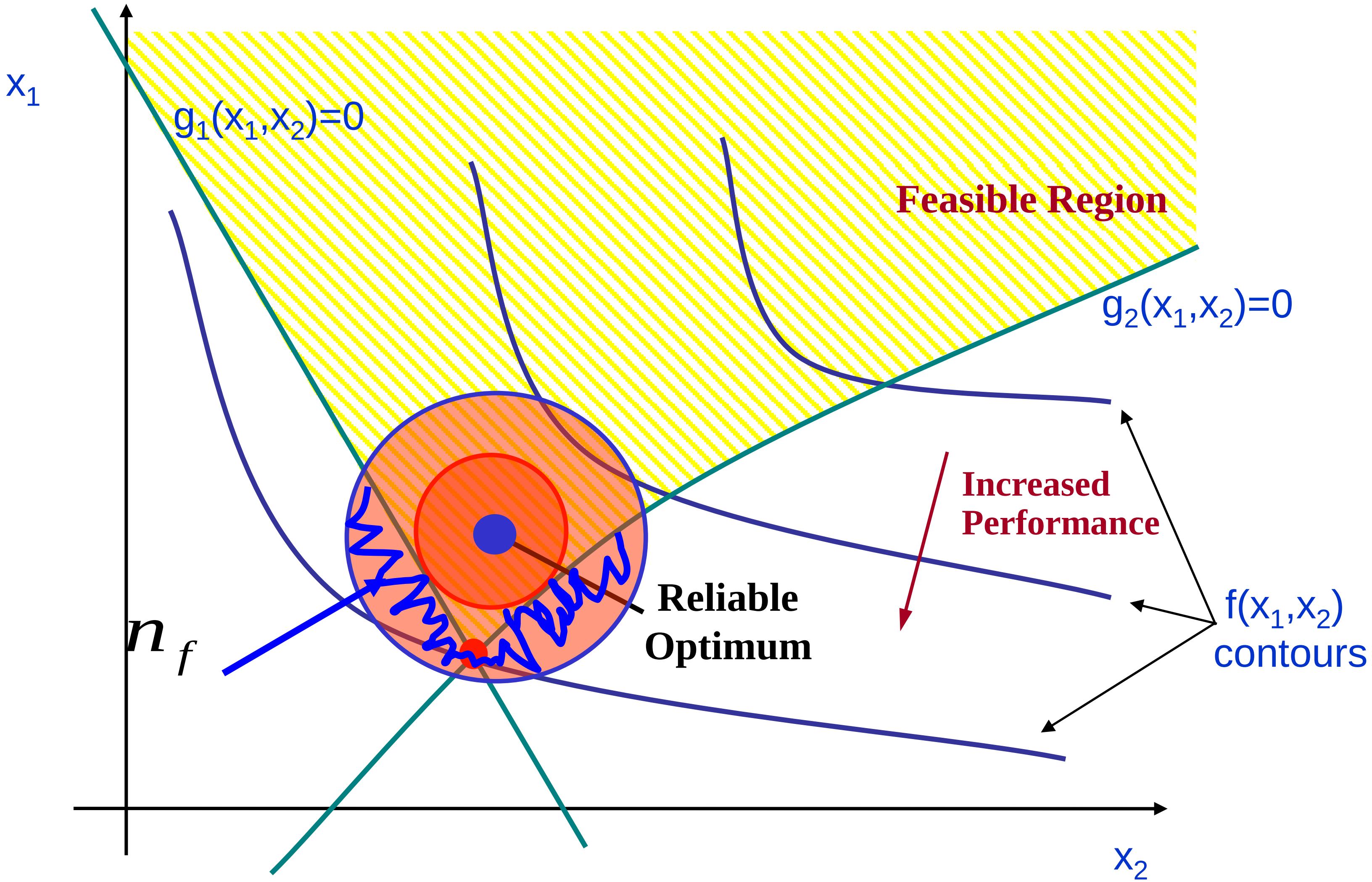
Quarter-Car Model: Results

Cumulative Probability of Failure for Threshold = 2G



Efficient MCS (blue) approach is close to true MCS results (red)

Principle of Importance Sampling: Random Variable Case



Importance Sampling for Random Process

Instantaneous Conditional Probability of Failure:

$$p_f^{\lambda}(t_i) = \int_{\Omega} \theta(\mathbf{x};t_i)\, f_{\mathbf{X}}(\mathbf{x};t_i)\, d\mathbf{x}$$

$\mathbf{x} = \{x_1, x_2, \ldots, x_i\}$ where x_i is a realization of R.V. $X_i = X(t_i)$

$$p_f^{\lambda}(t_i) = \int_{\Omega} \theta(\mathbf{x};t_i) \frac{f_{\mathbf{X}}(\mathbf{x};t_i)}{f_{\mathbf{X}^S}(\mathbf{x};t_i)} f_{\mathbf{X}^S}(\mathbf{x};t_i)\, d\mathbf{x}$$

Sampling Joint PDF

$$p_f^{\lambda}(t_i) = \frac{\sum_{n=1}^{N_s(t_{i-1})} \theta(\mathbf{x};t_i)\,\omega(\mathbf{x},t_i)}{N_S(t_{i-1})} = \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x},t_i)}{N_S(t_{i-1})}$$

Importance Sampling for Random Process

$$p_f^\lambda(t_i) = \frac{\sum_{n=1}^{N_s(t_{i-1})} \theta(\mathbf{x};t_i)\omega(\mathbf{x},t_i)}{N_S(t_{i-1})} = \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x},t_i)}{N_S(t_{i-1})}$$

$$\boxed{\lambda(t_i) = \lim_{\Delta t \to 0} \frac{p_f^\lambda(t_i)}{\Delta t} = \lim_{\Delta t \to 0} \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x},t_i)}{\Delta t \cdot N_S(t_{i-1})}}$$

$$\omega(\mathbf{x},t_i) = \frac{f_{\mathbf{X}}(\mathbf{x};t_i)}{f_{\mathbf{X}^S}(\mathbf{x};t_i)}$$: Likelihood ratio at t_i

$N_S(t_{i-1})$: Safe sample points at t_{i-1}

$N_f(t_i)$: Number of failures in $\Delta t = t_i - t_{i-1}$

Likelihood ratio:

$$\omega(\mathbf{x};t_i)=\frac{f_{\mathbf{X}}(\mathbf{x};t_i)}{f_{\mathbf{X}}^{S}(\mathbf{x};t_i)}=\frac{f_{\mathbf{X}}(x_i,x_{i-1},\ldots,x_{i-d})}{f_{\mathbf{X}}^{s}(x_i,x_{i-1},\ldots,x_{i-d})}$$

Decorrelation length : Maximum number of lags over which realizations of x_i are significantly correlated

$$x_i-\mu=\phi_1(x_{i-1}-\mu)+\phi_2(x_{i-2}-\mu)+\ldots..+\phi_p(x_{i-p}-\mu)+\varepsilon_i(N(0,\sigma_S{}^2))$$

To generate sampling PDF

$$f_{\mathbf{X}}(\mathbf{x})=\frac{1}{(2\pi)^{k/2}\,|\,\boldsymbol{\Sigma}\,|^{1/2}}\exp\left(-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^T\boldsymbol{\Sigma}^{-1}(\mathbf{x}-\boldsymbol{\mu})\right)$$

From Yule-Walker Eqs

Estimation of Safe Sample Functions

$$\lambda(t_i) = \lim_{\Delta t \to 0} \frac{\sum_{n=1}^{N_f(t_i)} \omega(\mathbf{x}, t_i)}{\Delta t \cdot N_S(t_{i-1})}$$

$$\boxed{\frac{\sigma_e}{\sigma_S} x_f > S_{threshold}}$$

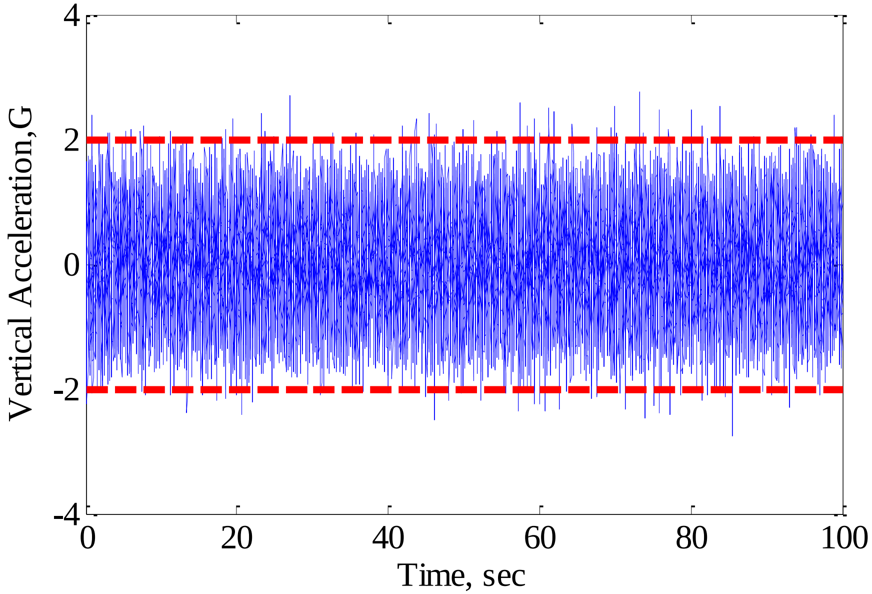
"Inflated" response

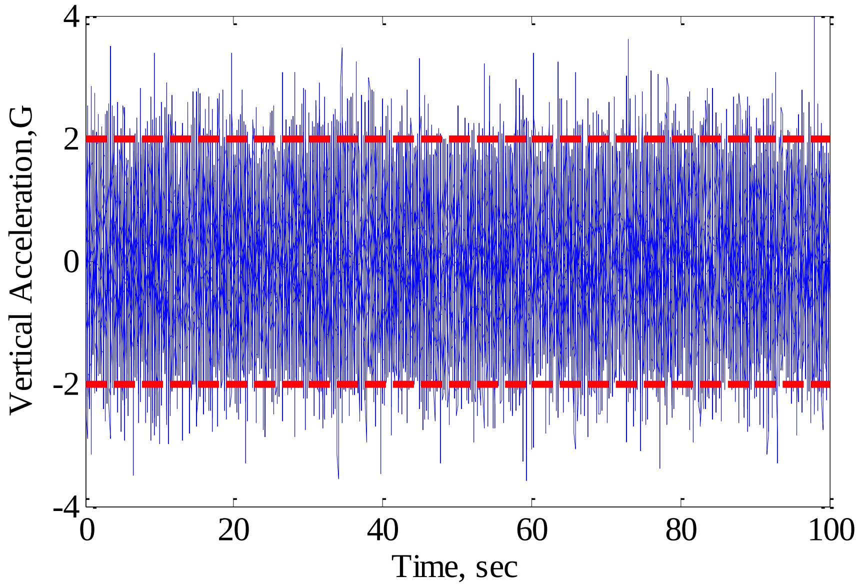
Quarter-Car Example

$$u_i = 1.2456u_{i-1} - 0.2976u_{i-2} - 0.1954u_{i-3} + \varepsilon_i(0, 0.5132^2)$$

Original PDF $\sigma_e = 0.51$

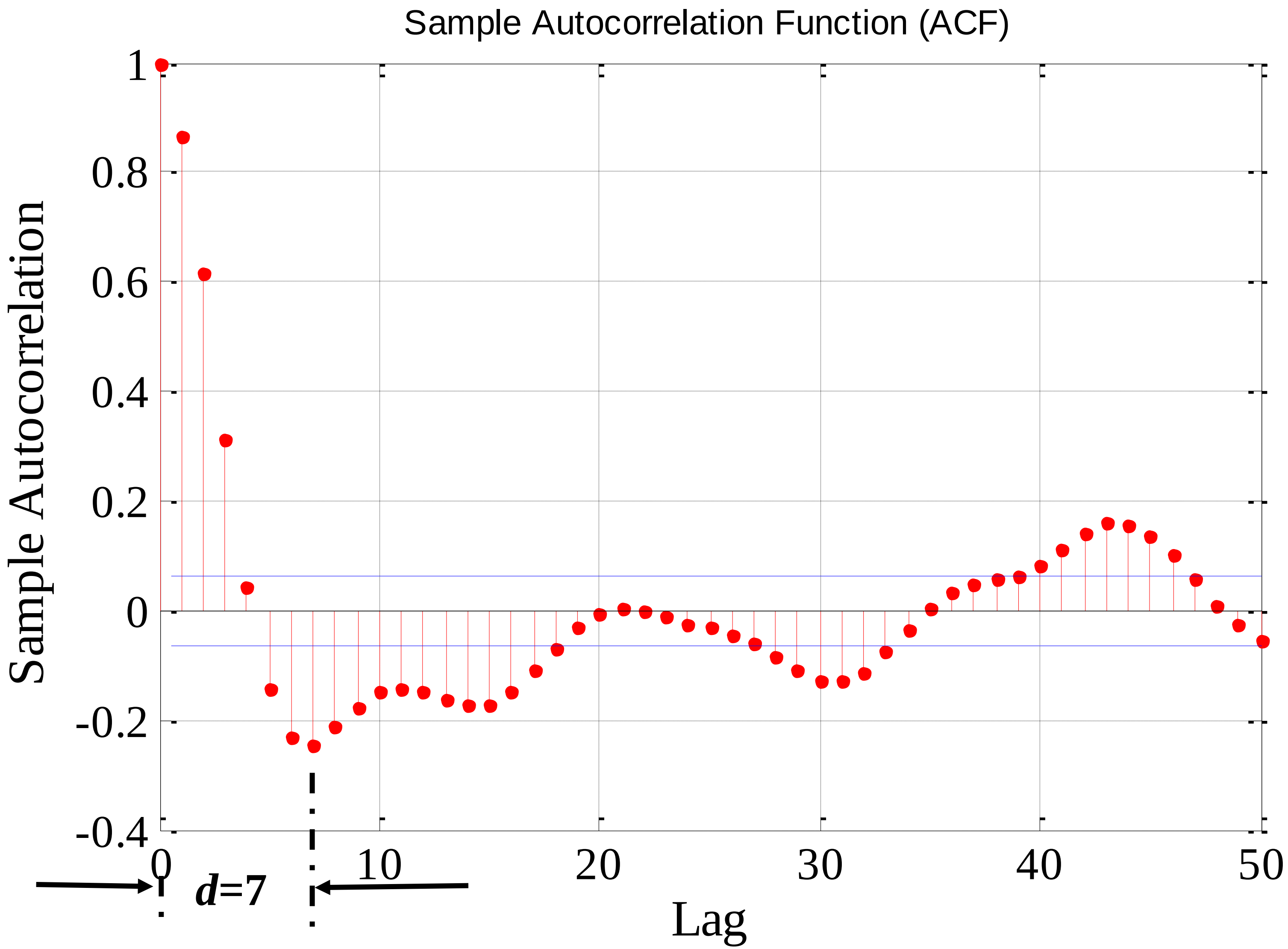
Sampling PDF $\sigma_s = 0.7$





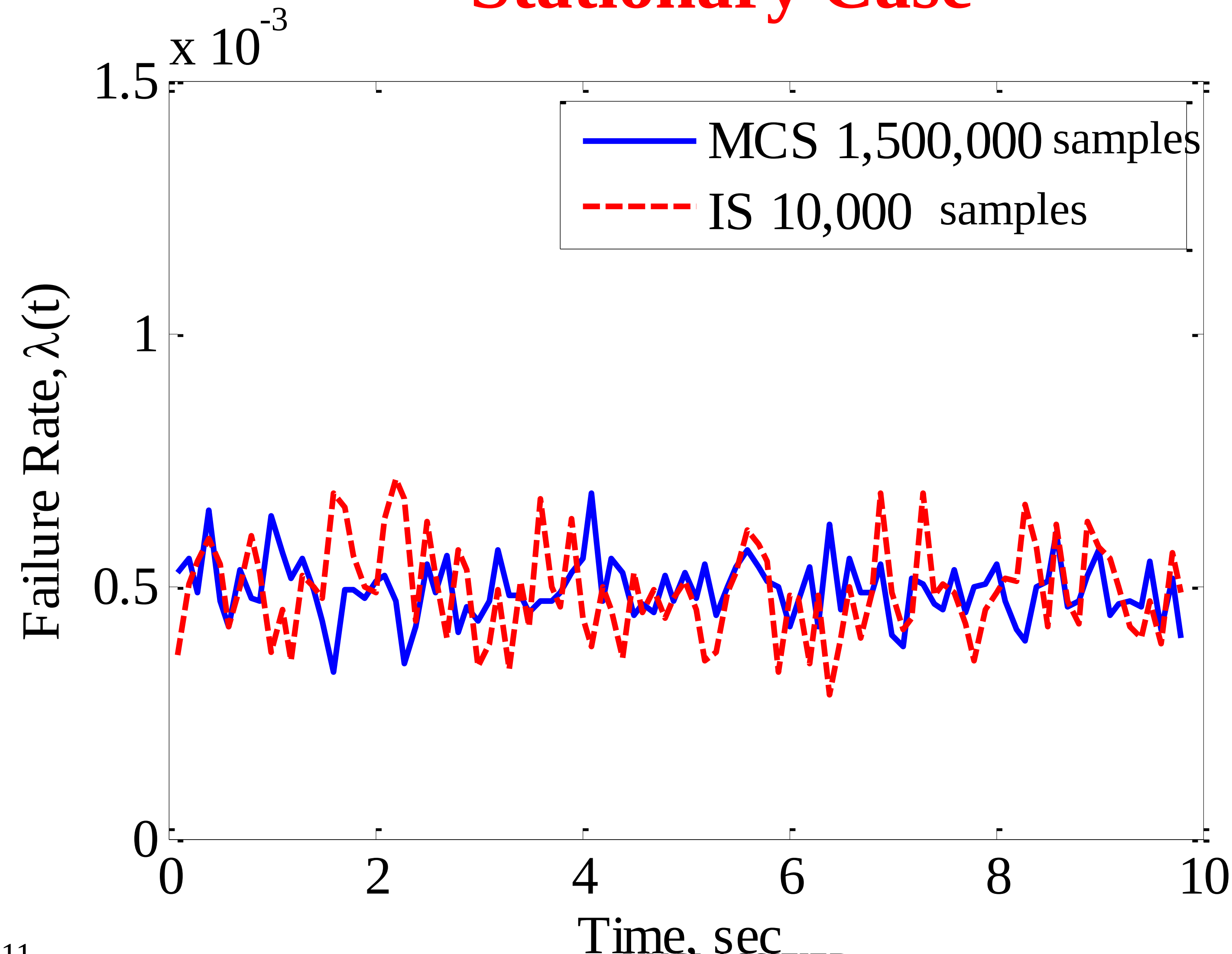
The sampling PDF results in more failures

Quarter-Car Example



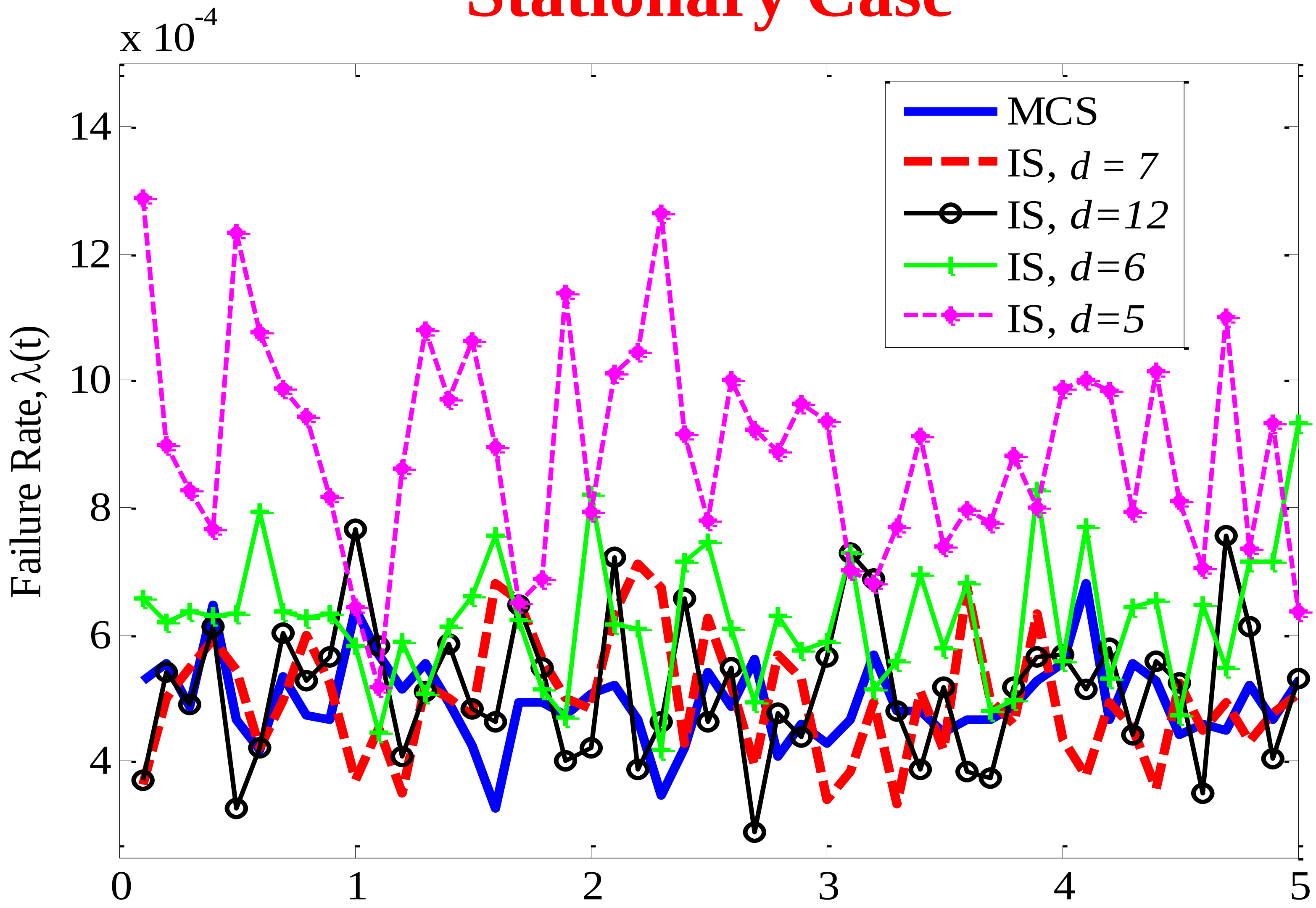
Quarter-Car Example

Stationary Case



Quarter-Car Example

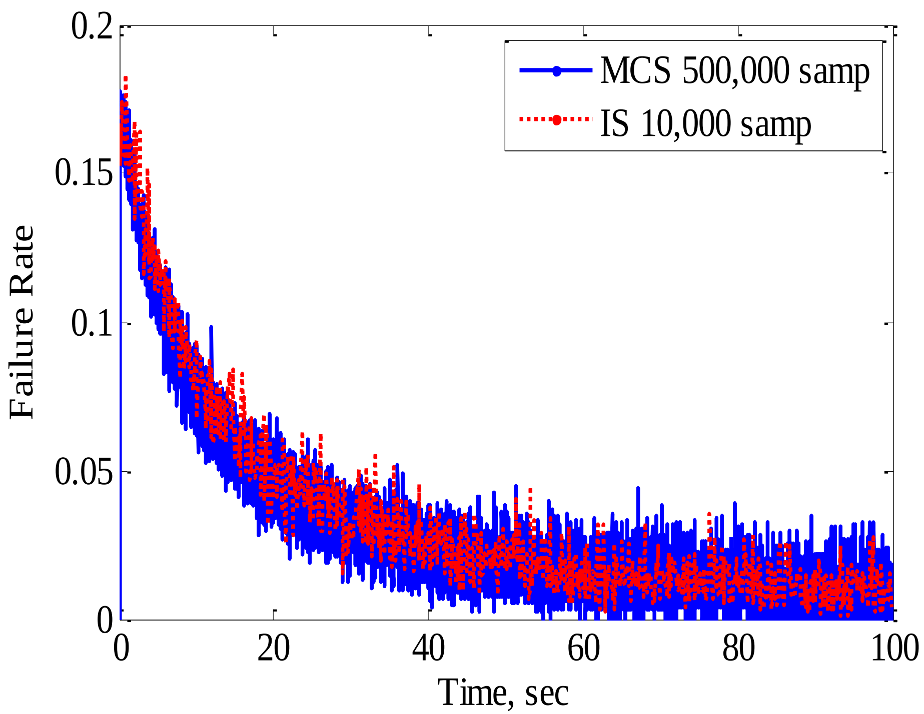
Stationary Case



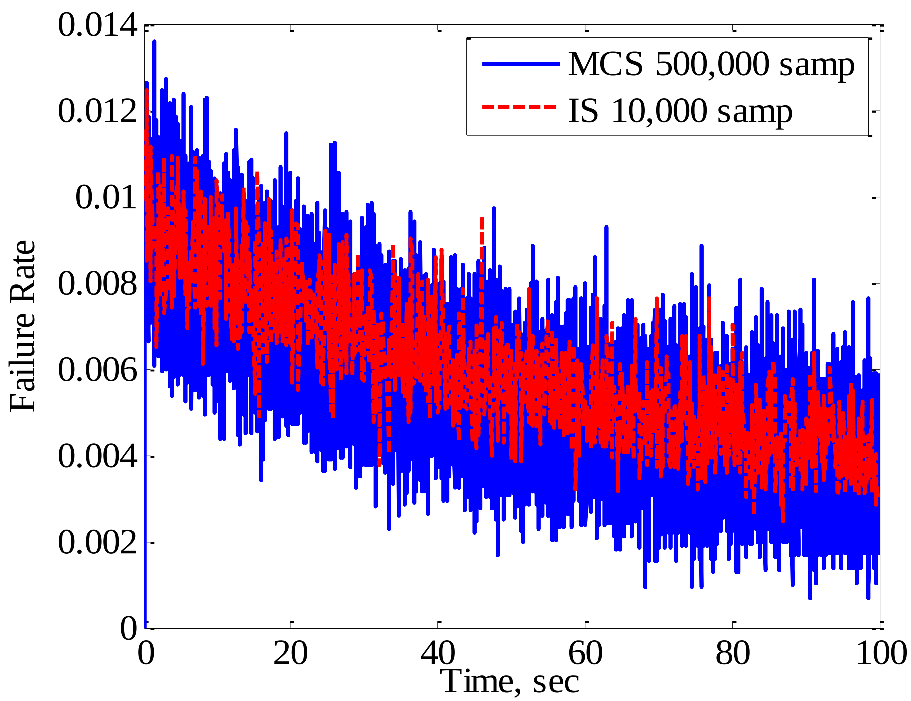
Quarter-Car Example

Non-Stationary Case

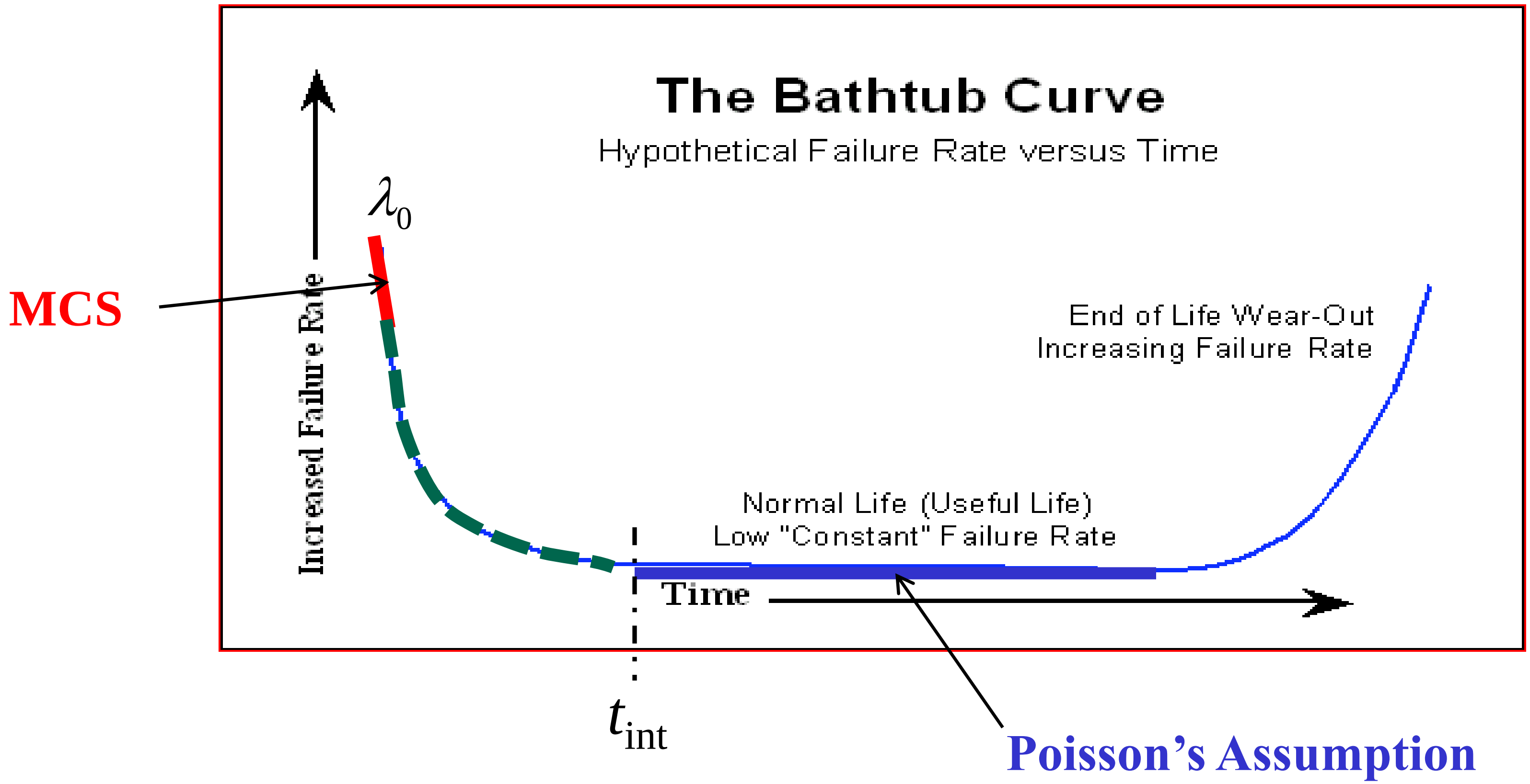
Threshold = 2 g



Threshold = 2.65 g



Observations / Practical Issues



- ➢ **Analytical methods can be used under the Poisson's assumption**
- ➢ **IS at initial time may need a few thousand output sample functions**

Ongoing Work Plan

- **Improve the current accelerated testing method based on importance sampling so that only 5-10 tests are needed (Q3)**
  - ✓ **Characterize the "inflated" output random process in importance sampling using "generalized" Kriging and MLE and/or time series**

- **Demonstrate the accelerated testing methodology using the N-post (or 4-post) Reconfigurable Road Simulator of the Physical Simulation Laboratory at TARDEC (Q3 and Q4)**

TARDEC N-post Reconfigurable Road Simulator

Thanks for your attention !

Q & A

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.