Common Cause Failure Parameters Quantification Using ICDE Database

Presenter: S. Yalaoui (CNSC)
Co-Authors:
S. Yu and M. Pandey (u Waterloo)
Y. Akl (CNSC)

University of Waterloo

CNSC CCSN

Outline

- **Context**
  - New developments in CCF modeling
  - ICDE project
- **Modeling of CCF**
  - Key ideas
  - General Multiple Failure Rate Model
- **Statistical Estimation**
  - Empirical Bayes method
- **Case Study**
  - MOVs
- **Summary**

Common Cause Failures (CCF)

- **CCF is a dependent failure**
  - in which two or more component fault states exist
  - simultaneously, or within a short time interval, as a direct result of a shared cause
- **CCF events can significantly impact the availability of safety systems of nuclear power plants**
- **ICDE project started in 1994**
  - systematically collecting and analysing CCF data

Objectives

- **Review status of the CCF modeling techniques**
  - Alpha factor, Multiple Greek letter and Binomial rate
- **Investigate the technical aspects of Empirical Bayes method**
- **Implement the methods for data mapping and statistical estimation of CCF rates**
- **Present case studies to illustrate the analysis of CCF data**
  - MOV data

Terminology

- $\mathit{\Lambda}_{k/n}$ = **Failure rate (system level)**
  - failure of ANY k out of *n* component
- $\lambda_{\mathbf{12}}$ = **Failure rate (component level)**
  - Failure of specific components 1 and 2
- **Symmetry assumption**
  - $\lambda_{12} = \lambda_{13} = \lambda_{13} = \lambda_{\mathbf{2/3}}$ same rate for dual failures
- **Combinatorial relations between system and component rates**
  - $\mathit{\Lambda}_{2/3} = 3\lambda_{2/3}$
  - $\mathit{\Lambda}_{k/n} = \binom{n}{k}\lambda_{k/n}$

Alpha Factors

- **$\alpha_{k/n}$ It is the ratio of the failure rate $\Lambda_{k/n}$ to the total rate Λ_n**
  - $\alpha_{k/n} = \frac{\Lambda_{k/n}}{\Lambda_n}$ and $\Lambda_n = \sum_{k=1}^{n} \Lambda_{k/n}$

Data Mapping

- **CCF data are sparse**
- **Probabilistic concepts are developed to borrow the data from CCG of different sizes**
- **The CCF data are mapped to a target system of CCG *n***
- **Mapping down**
  - Data from CCG > n
- **Mapping up**
  - Data from CCG < n

Statistical Estimation

Data

- **Population**
  - Number of systems susceptible to CCF
- **Exposure Time**
  - Duration during which CCF data are recorded
- **Number of failures**
  - Failures observed in the population
  - It is an involved task
- **Impairment states**
  - C = complete failure (1), D = degraded (0.5)
  - I = Incipient (0.1), W = working (0)
- **Impact Vector**
  - Probability of CCF failures under a demand and the observed impairment states

Estimation Methods

- **Two methods**
  - Maximum likelihood method (objective method)
  - Bayesian Method (subjective method)
- **Maximum Likelihood Estimation (MLE)**
  - Simple and straightforward method
  - Ample data are needed for robustness
  - $\hat{\lambda}_i = \frac{N_i}{T_i}$
  - Variance of the estimator $\sigma(\hat{\lambda}_i) = \sqrt{\frac{N_i}{{T_i}^2}}$

Empirical Bayes (EB)

- **A prior distribution is assigned to λ**
  - Gamma distribution (conjugate prior)
- **The posterior distribution of the failure rate is also a gamma distribution**
- **Mean and variance of the CCF data are used to calculate two parameters (α, β) of gamma dist.**
- **Challenge**
  - Pooling the data collected over different exposure time
  - Impact vector (uncertainty about CCF failures)

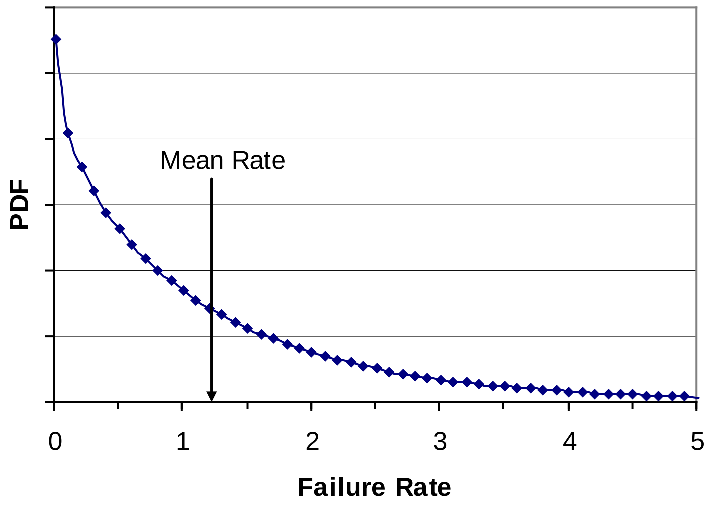
Examples

Illustrative Example - Data

i	N_i	T_i	MLE		Vaurio's EB		
			Mean	S.D.	w_i	Mean	S.D.
1	31	236.9020	0.1309	0.0235	0.1539	0.1343	0.0238
2	157	115.9440	1.3541	0.1081	0.1534	1.3532	0.1077
3	30	36.8120	0.8150	0.1488	0.1513	0.8229	0.1480
4	13	7.5970	1.7112	0.4746	0.1405	1.6664	0.4469
5	7	5.4660	1.2806	0.4840	0.1358	1.2723	0.4525
6	7	1.6890	4.1445	1.5665	0.1070	3.2439	1.1536
7	0	1.1230	0.0000	0.0000	0.0926	0.4846	0.5089
8	0	0.5520	0.0000	0.0000	0.0655	0.6974	0.7323

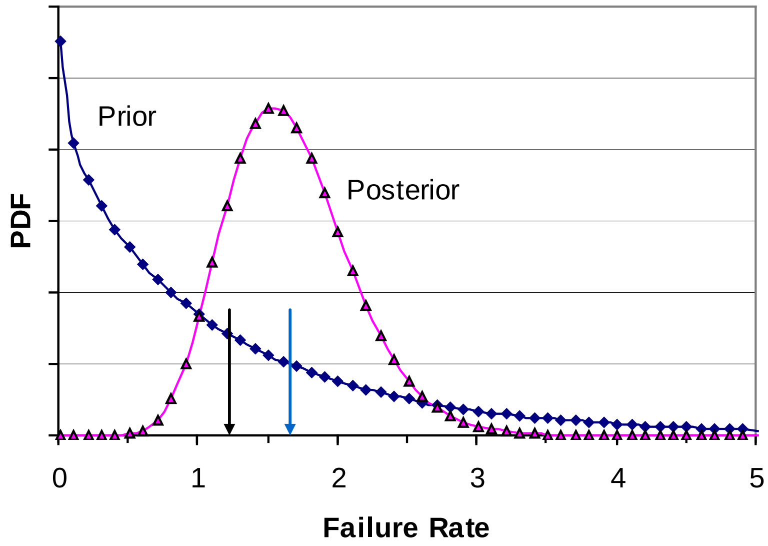
Example-EB Prior

- **Prior distribution estimated by EB**
  - $\alpha = 0.907$, $\beta = 0.7485$
  - Mean failure rate = 1.2 failures/time
  - Standard deviation = 1.27 failures/time



Example-Bayesian Updating

- **Posterior of failure rate of system 4**
  - Prior $\alpha = 0.907$, $\beta = 0.7485$
  - Data: $N_i = 13$, $T_i = 7.597$
  - Posterior mean rate = 1.66 failures/time
  - Posterior SD = 0.44 failures/time

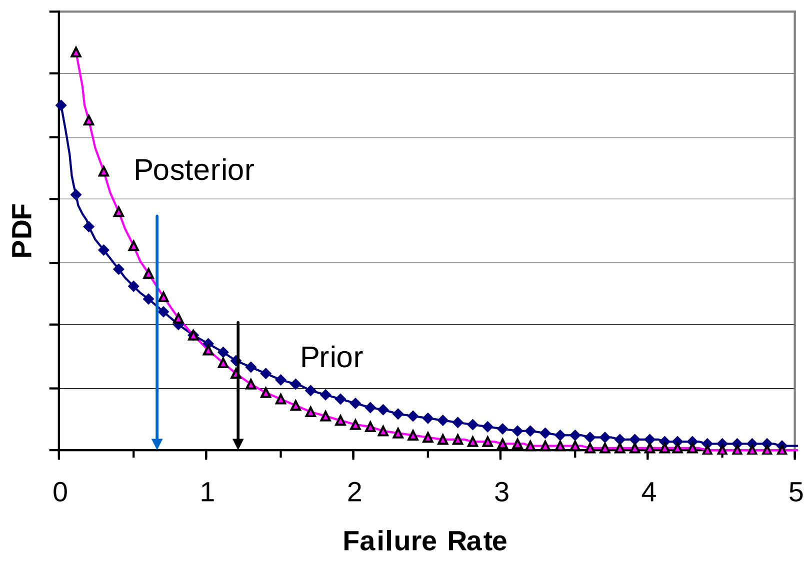


Posterior failure rate

Median	1.62
5th percentile	1.0
95th percentile	2.46

Example-Bayesian Updating

- **Posterior of system 8**
  - Prior $\alpha = 0.907$, $\beta = 0.7485$
  - Data: $N_i = 0$, $T_i = 0.552$
  - Posterior mean rate = 0.7 failures/time
  - Posterior SD = 0.73 failures/time



Posterior failure rate

Median	0.464
5th percentile	0.027
95th percentile	2.162

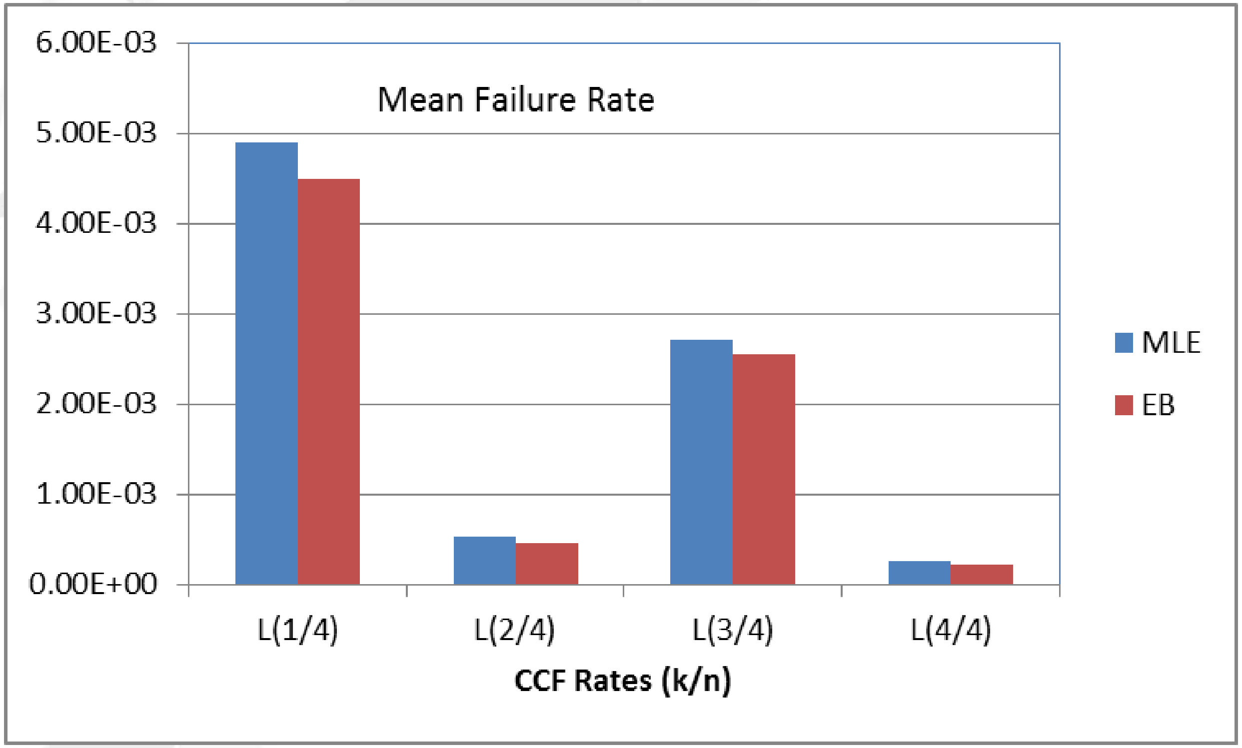
Illustrative Case Study

- **Data**
  - Sample similar to that of motor operated valves (MOV) in nuclear safety systems
  - A system of CCG of 4 is considered, data mapping was performed

System size		Number of failures $N_{k/n}$					
n		$1/n$	$2/n$	$3/n$	$4/n$	$5/n$	$6/n$
2	original	36	1	0	0	0	0
	mapped	36	0.6400	0.3200	0.0400	0	0
4	original	18	2	10	1	0	0
	mapped	18	2	10	1	0	0
8	original	6	1	0	0	0	0
	mapped	3.5714	0.2143	0	0	0	0
16	original	13	1	0	0	0	1
	mapped	4.0456	0.4209	0.1099	0.0082	0	0
sum	mapped	61.6170	3.2752	10.4299	1.0482		

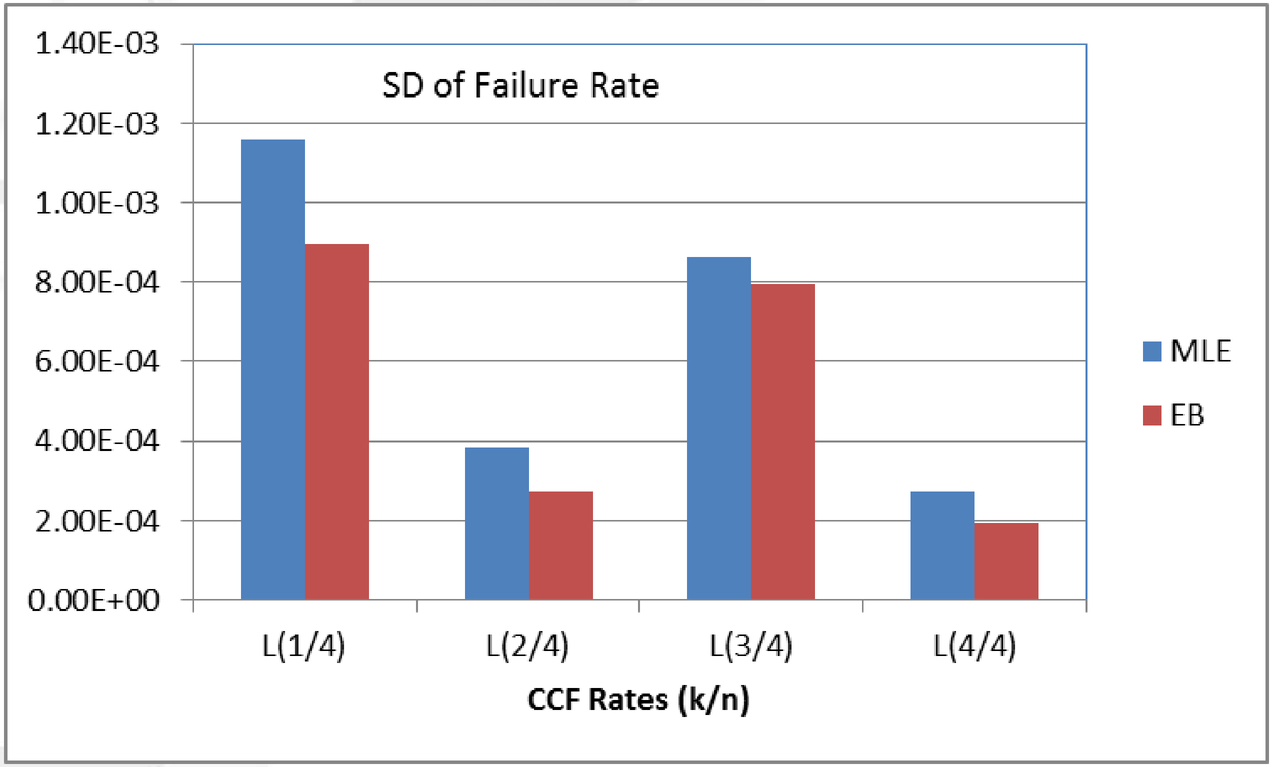
Results-1

- Comparison of MLE and EB

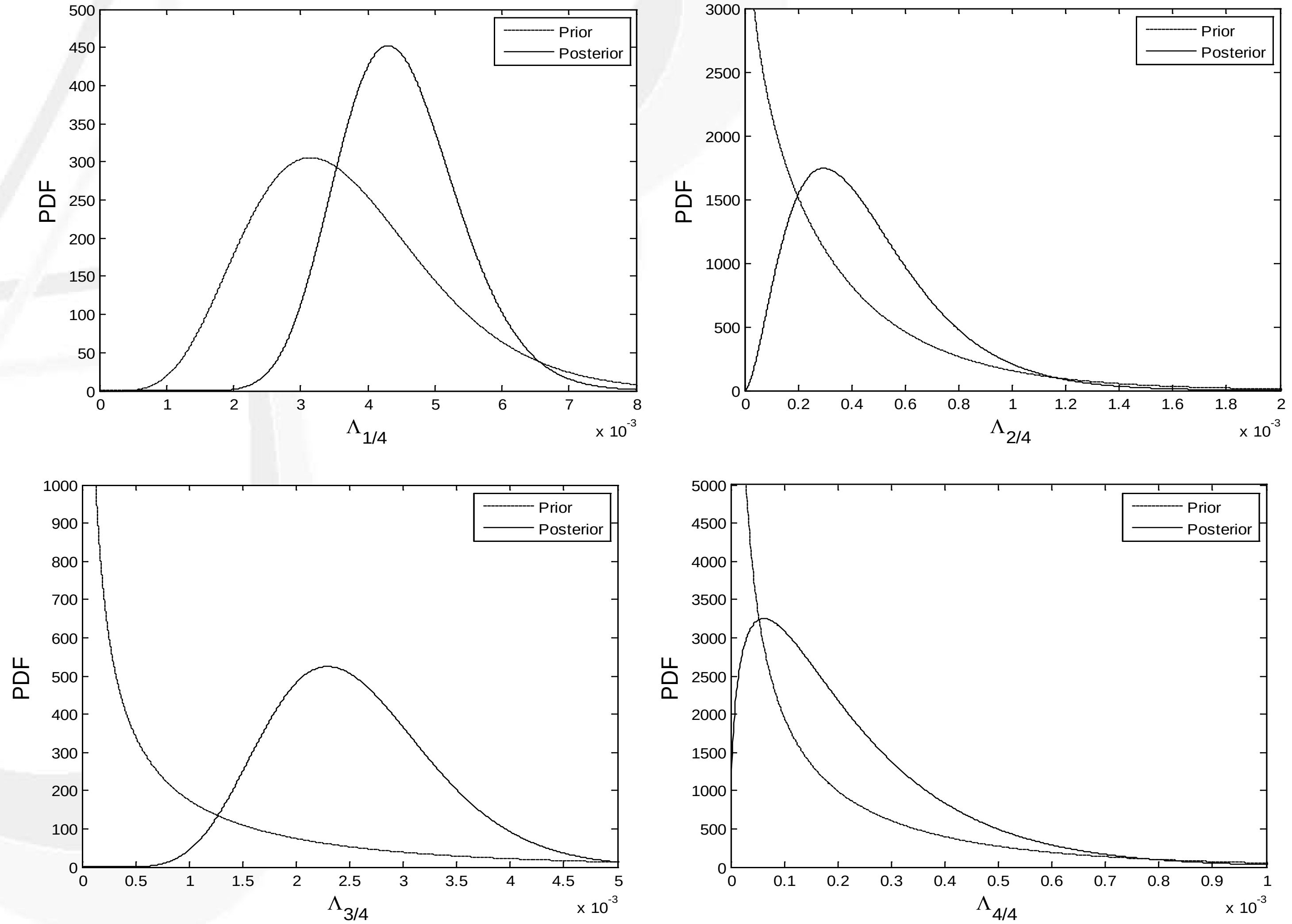


Results-2

- Comparison of standard deviations



Posterior Distributions (EB)



Summary

- **Application of CCF models and data mapping method to ICDE data**
- **"General multiple failure rate model" for modeling CCF data**
- **Investigation of statistical estimation methods**
  - Empirical Bayes (EB)
- **A case study is presented**

Concluding Remarks

- This project demonstrates the development of a capacity to analyze CCF rates using the Empirical Bayesian (EB) method
- Bayesian approach is a logical and consistent way to analyze problems confounded by “uncertainties”
- Empirical Bayes allows to pool the data from different CCGs and plants
- Implementation of EB method in practice is feasible (Excel-based programs)

Recommendations

- **More case studies considering real data from plant safety systems should be undertaken**
- **The impact of testing scheme, such as staggered testing, should be considered**

Thanks for your attention