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Interagency (ERDC & USACE Headquarters) Workshop on Asset Management for Civil Works Infrastructure, August 23-24, 2005, Alexandria, VA

Optimal Maintenance of Civil Infrastructure Systems

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OBJECTIVES OF THE WORKSHOP

- DEFINE ASSET MANAGEMENT (AM) AND METRICS
- DISCUSS CURRENT AND FUTURE CHALLENGES RELATED TO AM
- PROVIDE INTERAGENCY FORUM FOR SHARING LESSONS LEARNED
- EVALUATE APPLICABILITY OF EXISTING TOOLS AND DATA REQUIREMENTS
- IDENTIFY TECHNICAL GAPS AND CORRESPONDING R&D REQUIREMENTS

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Deterioration, Corrosion, …

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OVERVIEW

- MAINTENANCE MODELS
- CONDITION, SAFETY AND COST INTERACTION
- COMBINATION AND OPTIMIZATION OF MAINTENANCE ACTIONS
- BRIDGE NETWORK ANALYSIS
- NETWORK OPTIMIZATION USING GA
- INTEGRATION OF MONITORING IN MANAGEMENT

CURRENT CONDITIONS OF BRIDGE STOCK (in the United States)

- 50% of bridges are over 50 years old
- Each year 5000 bridges become classified as deficient
- 125,000 bridges are rated as structurally deficient (20% of 600,000 bridges in the federal inventory)

INVESTMENTS (in the United States)

1. FHWA

- $1trillion investment in highways and bridges

2. ASCE's Infrastructure Report Card

- Nation's Infrastructure Receives a D in 2005

LIMITATIONS OF CURRENT BMSs

- Subjective assessment (visual inspection) and empirical transition models are used (condition state)
- Bridge system performance is not generally addressed (element level, single failure mode)
- Bridge reliability and optimization are not directly incorporated

AASHTO LRFD BRIDGE DESIGN SPECIFICATIONS (1993, 1998, 2003…)

- Level 1 Reliability-based limit states

Areas suggested by authorities for future development

- More emphasis on system rather than component reliability
- Development of larger and more precise database
- Inclusion of aging and deterioration models

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Maintenance Models

with J.S. Kong

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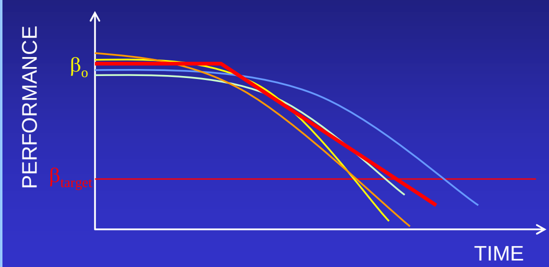
RELIABILITY PROFILES OF SIMILAR BRIDGES



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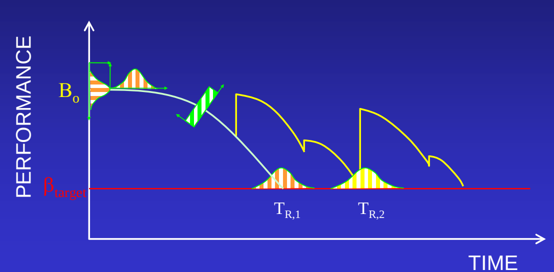
BRIDGE RELIABILITY PROFILE



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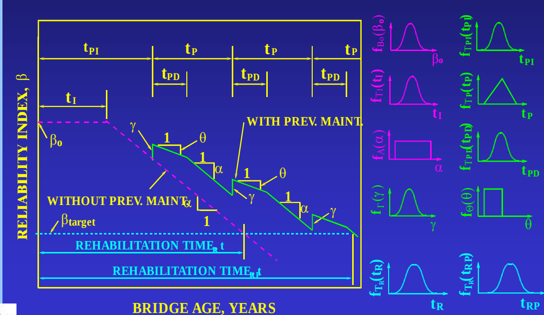
RELIABILITY INDEX PROFILE MODEL AND ASSOCIATED RANDOM VARIABLES



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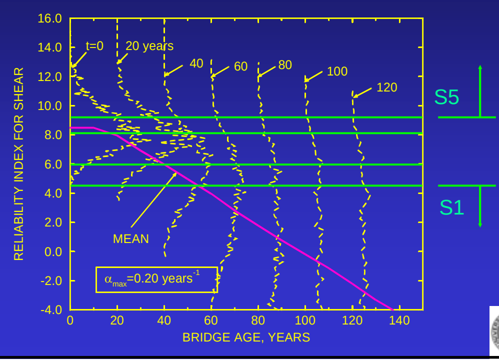
TIME VARIATION OF THE DISTRIBUTION OF RELIABILITY INDEX (SHEAR)



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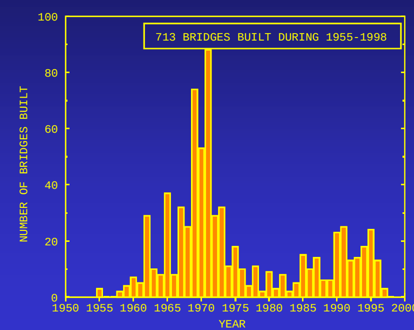
NUMBER OF BRIDGES BUILT DURING 1955 - 1998



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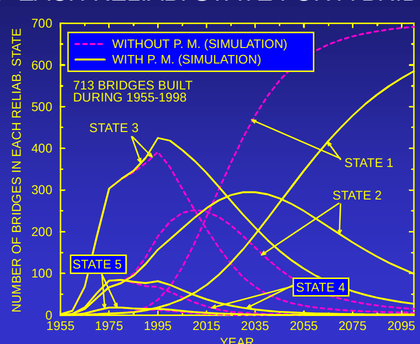
VARIATION IN TIME OF THE PROBABILITY OF EACH RELIAB. STATE FOR A BRIDGE



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FIXED MAINTENANCE COST

[Maunsell Report 1999]

Cost Type	Without Prev. Maint.	With Prev. Maint.
Prev. Maint. Cost	0	92
Rehabilitation Cost	677	265
User Cost for Prev. Maint.	0	124
User Cost for Rehabilitation	2141	403

Pounds Sterling / m^2 of deck area

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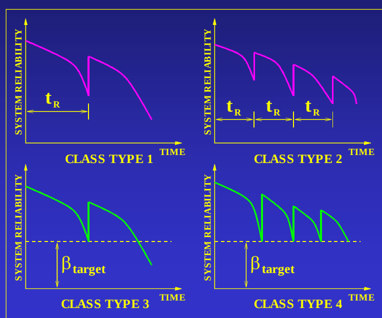
TIME-CONTROLLED AND RELIABILITY CONTROLLED MAINTENANCE ACTIONS



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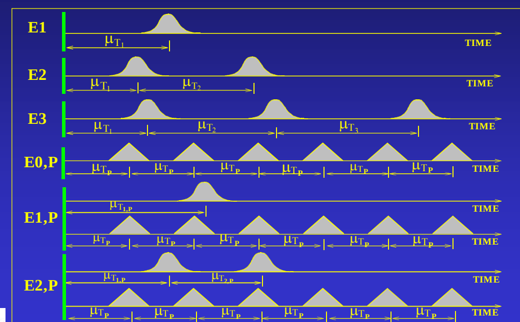
DESIGN VARIABLES ASSOCIATED WITH DIFFERENT SCENARIOS (Time-Controlled)



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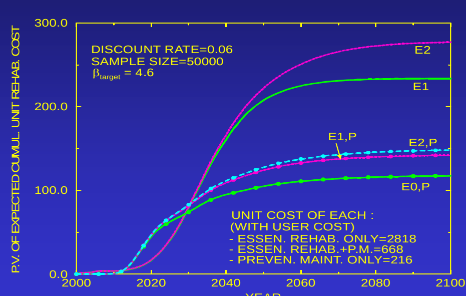
COMPARISON OF P.V. OF EXP. CUMUL. REHAB. COST



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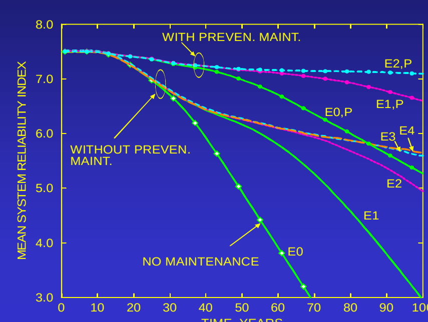
MEAN SYSTEM RELIABILITY INDEX PROFILE ASSOCIATED WITH DIFFERENT MAINTENANCE SCENARIOS



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Condition, Safety and Cost Interaction

with L.C. Neves

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CONDITION DEFINITION

CONDITION INDEX

- 0 – NO CHLORIDE CONTAMINATION
- 1 – ONSET OF CORROSION
- 2 – ONSET OF CRACKING
- 3 – LOOSE CONCRETE/ SIGNIFICANT DELAMINATION

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"SAFETY" DEFINITION

SAFETY INDEX DEFINED BY THE LOAD CAPACITY FACTOR, *S* (ALSO DENOTED AS *K)*

$S = 0.91$ MINIMUM ACCEPTABLE THRESHOLD

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MAINTENANCE INTERVENTIONS

S1: Minor concrete repairs

S2: Silane

S3: Rebuild

S4: Cathodic protection

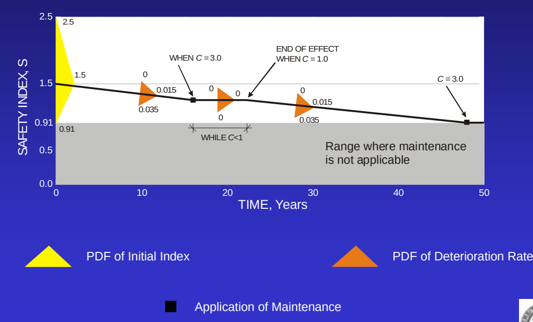
S5: Replace expansion joints

Essential Maint. (S1, S3)

All condition, safety, maintenance, and cost data for both overbridge and underbridge was provided by Parsons Brinkerhoff Ltd., Bristol, U.K. (Dr. Steven Denton), December 2002- January 2003.

Minor Concrete Repair – Condition Profile

Minor Concrete Repair – Safety Profile



MAINTENANCE INTERVENTIONS

Maintenance Intervention	Effect on Condition Index				Effect on Safety Index			
	Improv. γ_C	Delay in Deterioration T_{dc} (years)	Deterioration Rate During Effect θ_C (year^{-1})	Duration of Maint. Effect T_{pdc} (years)	Improv. γ	Delay in Deterio-ration T_d (years)	Deterioration Rate During Effect θ (year^{-1})	Duration of Maint. Effect T_{pd} (years)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
S1 - Minor Concrete Repair	to 0.5	0	---	---	0	0 6.25 50	---	---
S2 – Silane	0	0	0 0.01 0.03	7.5 10 12.5	0	0	0 0.007 0.018	7.5 10 12.5
S3 – Do Nothing and Rebuild	to 0	10 15 30	---	---	1 1.25 1.5	16.25 27.5 50	---	---
S4 – CP	0	12.5	---	---	---	12.5	---	---
S5 – Replace Expansion Joints	0	0	0 0.04 0.08	10 15 30	0	0	0 0.007 0.018	10 15 30

MAINTENANCE INTERVENTIONS

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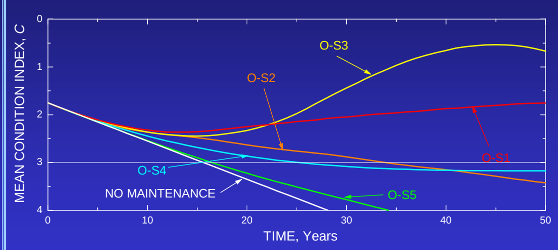
S5 – Replace Expansion Joints	0	0	0 0.04 0.08	10 15 30	0	0	0 0.007 0.018	10 15 30

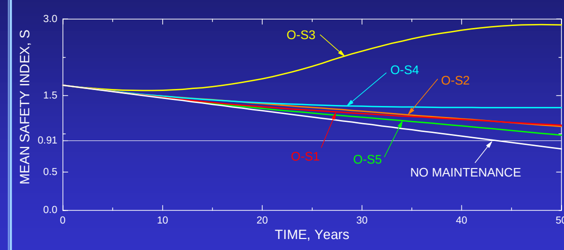
improves significantly the condition and delays the safety

Mean Condition Profile
Time-Based Strategy
Comparison of Five Strategies



O-S1: MINOR CONCRETE REPAIR
O-S2: SILANE
O-S3: REBUILD
O-S4: CATHODIC PROTECTION
O-S5: REPLACE EXPANSION JOINTS

Mean Safety Profile
Time-Based Strategy
Comparison of Five Strategies



O-S1: MINOR CONCRETE REPAIR
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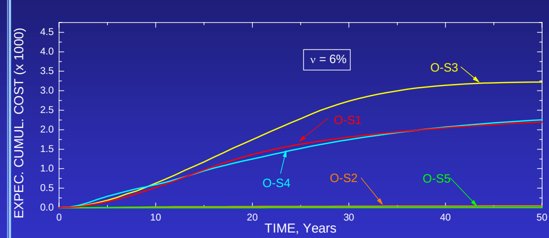
O-S5: REPLACE EXPANSION JOINTS

Expected Cost Profile ν=6%
Time-Based Strategy
Comparison of Five Strategies



O-S1: MINOR CONCRETE REPAIR
O-S2: SILANE
O-S3: REBUILD
O-S4: CATHODIC PROTECTION
O-S5: REPLACE EXPANSION JOINTS

Combination and Optimization of Maintenance Actions

with A. Petcherdchoo

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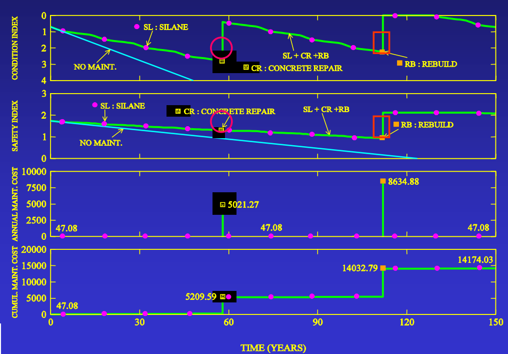
ONE REALIZATION OF CONDITION , SAFETY, AND COST FOR SL + CR + RB, ν =0%



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OPTIMIZATION FOR COMBINATION OF DIFFERENT MAINTENANCE ACTIONS

OPTIMIZATION PROBLEM

Design Variables : $\mu(t_{PI})$ and $\mu(t_P)$

(Mean of First and Subsequent Application Time of Preventive Maintenance)

Objective Function : **Minimum $C_T(t_{obj} = 50)$**

(Minimum of total cumulative maintenance cost over 50 years)

where $C_T = C_{T,PM} + C_{T,EM}$

$$= \int_0^{t_{obj}} C_{PM}(t_{PM})dt + \int_0^{t_{obj}} C_{EM}(t_{EM})dt$$

$$t_{PM} = t(t_{PI} \text{ or } t_P)$$

$$t_{EM} = t(C = C_{target} \text{ or } S = S_{target})$$

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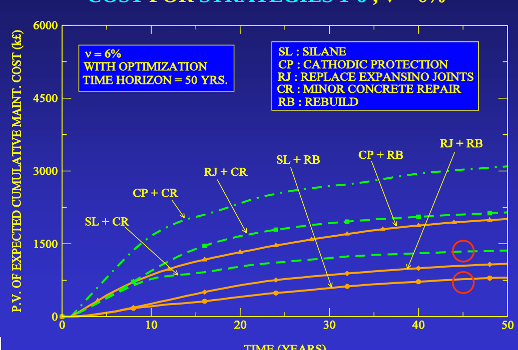
OPTIMAL P.V. OF EXPECTED CUMUL. MAINT. COST FOR STRATEGIES 1-6 ; ν = 6%



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Bridge Network Analysis

with F. Agkul

Selected Highway Bridge Network

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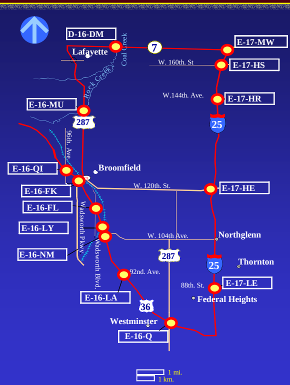

Characteristics of the Colorado Highway Bridges in the Network

Concrete Box Girder Continuous Prestressed

Concrete on Rolled I-beam Continuous

Welded Girder Komposite

Bridge Name	Bridge Type	CDOT Designation	Number Of Spans	Length (ft)	Width (ft)	Year Built
D-16-DM	Prestressed	CBGCP	2	146.0	46.5	1990
E-16-MU	Prestressed	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
E-16-QI	Prestressed	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
E-16-FK	Steel I-Beam	CIC	4	227.0	34	1951
E-16-FL	Steel I-Beam	CIC	4	177.0	34	1951
E-16-LY	Prestressed	CBGC	3	243.7	112	1985
E-16-NM	Prestressed	CPG	2	212.0	92	1991
E-16-LA	Prestressed	CIC	2	255.5	128.5	1983
E-16-Q	Steel I-Beam	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
E-17-MW	Prestressed	WGK	[illegible]	[illegible]	[illegible]	[illegible]
E-17-HS	Steel Plate Girder	WGK	4	211.7	34	1963
E-17-HR	Steel Plate Girder	WGK	4	209.8	34	1962
E-16-HE	Steel Plate Girder	WGK	4	222.2	34	1962
E-16-LE	Steel Plate Girder	WGK	4	225.0	64.5	1972

Developed Software Architecture

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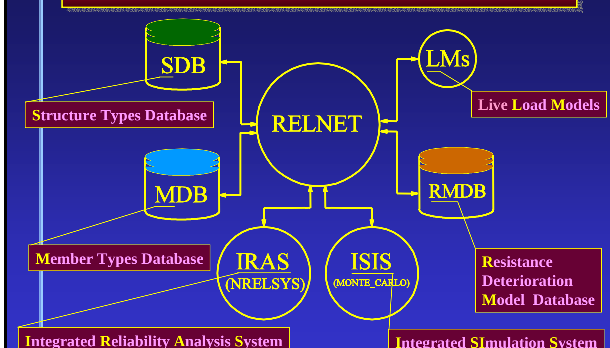

Structural Reliability Theory

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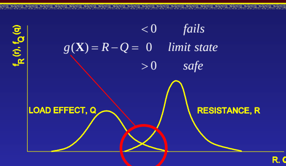
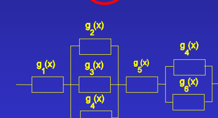
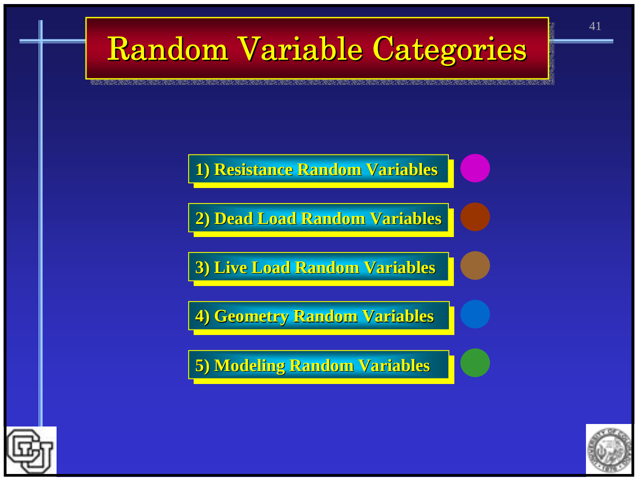
$$g(\mathbf{X}) = R - Q = \begin{cases} < 0 & \textit{fails} \\ 0 & \textit{limit state} \\ > 0 & \textit{safe} \end{cases}$$





$$P_f = P\left(\bigcup_{i=1}^{n} \bigcap_{j=1}^{m_i} \{ g_{ij}(\mathbf{X}) \le 0 \} \right)$$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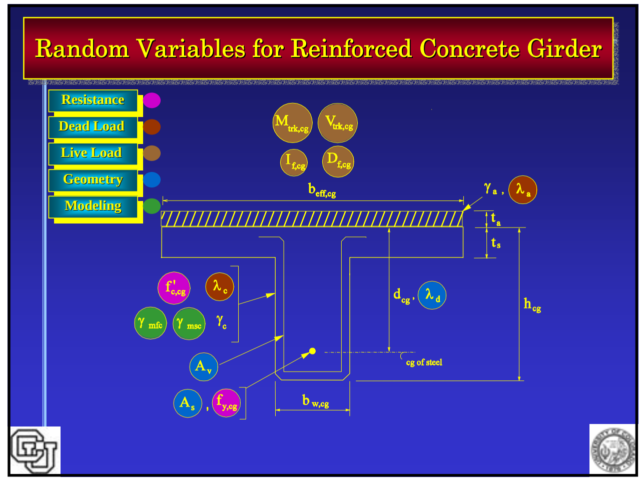
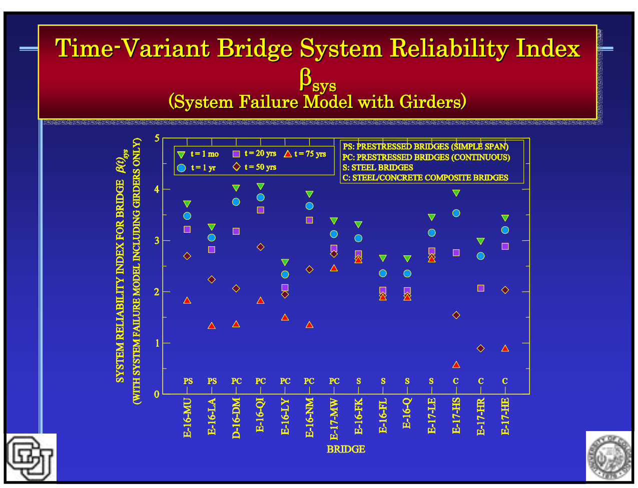
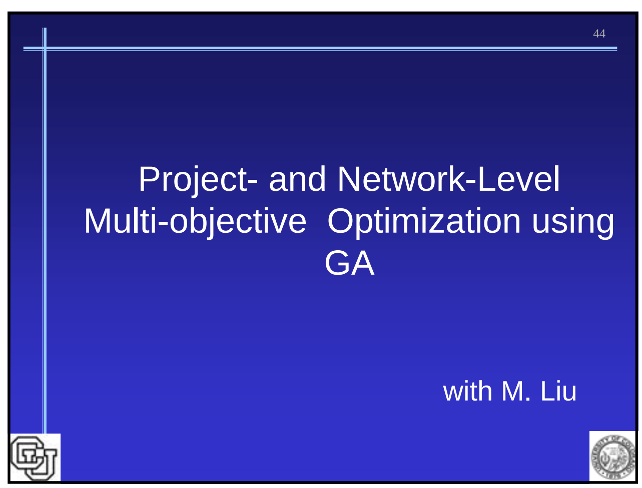
Random Variable Categories
1) Resistance Random Variables
2) Dead Load Random Variables
3) Live Load Random Variables
4) Geometry Random Variables
5) Modeling Random Variables


Random Variables for Reinforced Concrete Girder
Resistance
Dead Load
Live Load
Geometry
Modeling
cg of steel


Time-Variant Bridge System Reliability Index
βsys
(System Failure Model with Girders)
PS: PRESTRESSED BRIDGES (SIMPLE SPAN)
PC: PRESTRESSED BRIDGES (CONTINUOUS)
S: STEEL BRIDGES
C: STEEL/CONCRETE COMPOSITE BRIDGES
BRIDGE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Project- and Network-Level Multi-objective Optimization using GA
with M. Liu

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Life-cycle cost analysis

- Produces cost-effective engineering solutions that address in monetary terms various sources of expenses including design, construction, operation, inspection, maintenance, repair, and damage/failure consequences over a designated time-horizon.
- It is naturally interwoven with optimization techniques and probabilistic analysis.

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Single vs. Multi-objective Optimization for BMSs

- Single optimal maintenance solution may not always satisfy requirements of different bridge managers.
- The use of minimum expected LCC solutions might lead to situations where a small further investment leads to much better performance.
- Considering different performance criteria simultaneously, through multi-objective optimization, results in a set of alternative optimum maintenance solutions, producing the best possible tradeoffs among all competing objectives.

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Example 1:Multi-objective optimization of a group of existing RC elements

- *Goal* To determine a set of optimized tradeoff maintenance solutions while
- (1) minimizing the largest (i.e., worst) condition index,
- (2) maximizing the smallest (i.e., worst) safety index, and
- (3) minimizing the P.V. cumulative life-cycle maint. cost.

- *Subject to* (1) Condition $\leq$ 3.0
- (2) Safety $\geq$ 0.91.

- *Design variables*
- Years of maintenance applications and their respective types.

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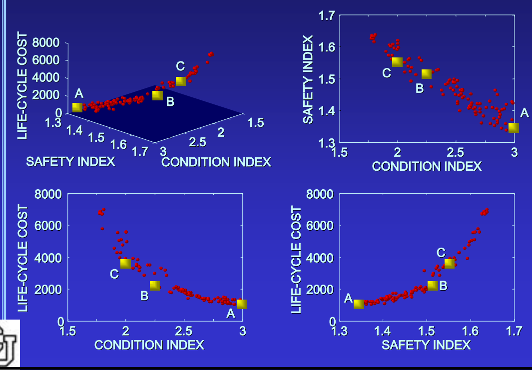
Performance Measures

- **Condition index**
- **Safety index**
- **Present value of cumulative life-cycle maintenance cost**

Optimized tradeoff solutions at 20th GA gen.



Performance profiles of three representative solutions

ID	Cond.	Safety	LCC
A	2.99	1.35	1031.8
B	2.26	1.51	2181.0
C	1.99	1.54	3574.5

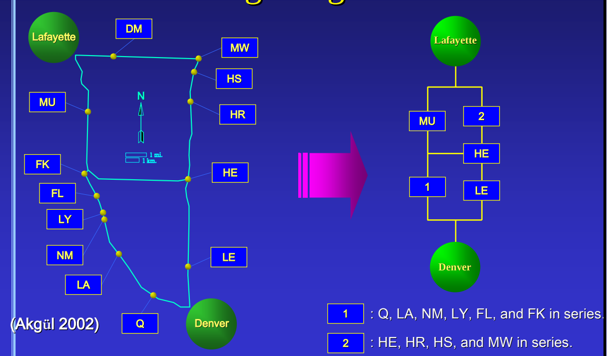
Example 2: network-level maintenance planning

Under budget constraints, it is important to prioritize maintenance needs to bridges that are more significant to the functionality of the entire network, in addition to scheduling these maintenance actions over the specified time horizon in order to achieve the overall cost-effectiveness.

Problem statement

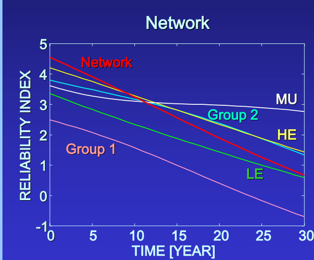
- The overall bridge network performance is measured by the reliability of connectivity between the origin and destination locations. It is computed in terms of time-dependent system reliability profiles of individual bridges that form the network.
- The present value of total expected life-cycle maintenance cost is considered as another conflicting objective subject to simultaneous minimization.

An existing bridge network



(Akgül 2002)

Reliability profiles of bridge deck slabs under no maintenance (1)

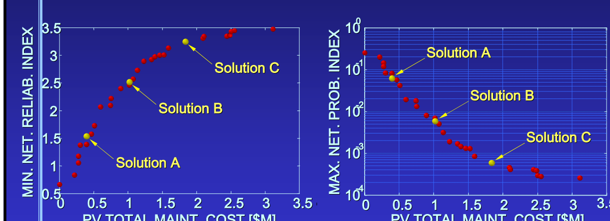


- Deterioration of concrete deck slabs is caused by the deicing chemicals related corrosion.
- Its propagation in concrete is predicted by Fick's law of diffusion.
- Effects of corrosion are gradual reduction of reinforcement area.

Four maintenance types

No.	Maintenance type	Reduction of deterioration rate α (year^{-1})	Improvement of system reliability index $\Delta\beta$	Unit cost (\$/m^2)
1	Resin injection	0.03 (with a duration of 15 years)	0	200
2	Slab thickness increasing	0	0.7	300
3	Steel plate attaching	0	2.0	600
4	Replacement	0	Back to initial reliability level	900

Optimized tradeoff solutions at 50th gen.



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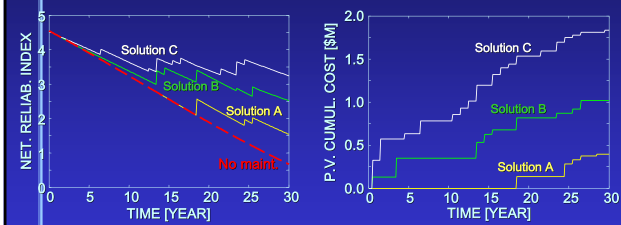
Three representative maintenance solutions



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Integration of Monitoring in Management

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CONCLUSIONS

The analysis of the interactions between condition, rating, safety and cost of deteriorating structures is a very complex process, and research in this area is still in its infancy.

Further research and gathering of data is necessary to make the incorporation of these interactions in structure maintenance and asset management systems possible.

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Thank You !