DISSERTATION DEFENSE

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AN INTEGRATED APPROACH TO TRANSPORTATION INFRASTRUCTURE MANAGEMENT

By

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PRESENTATION OUTLINE

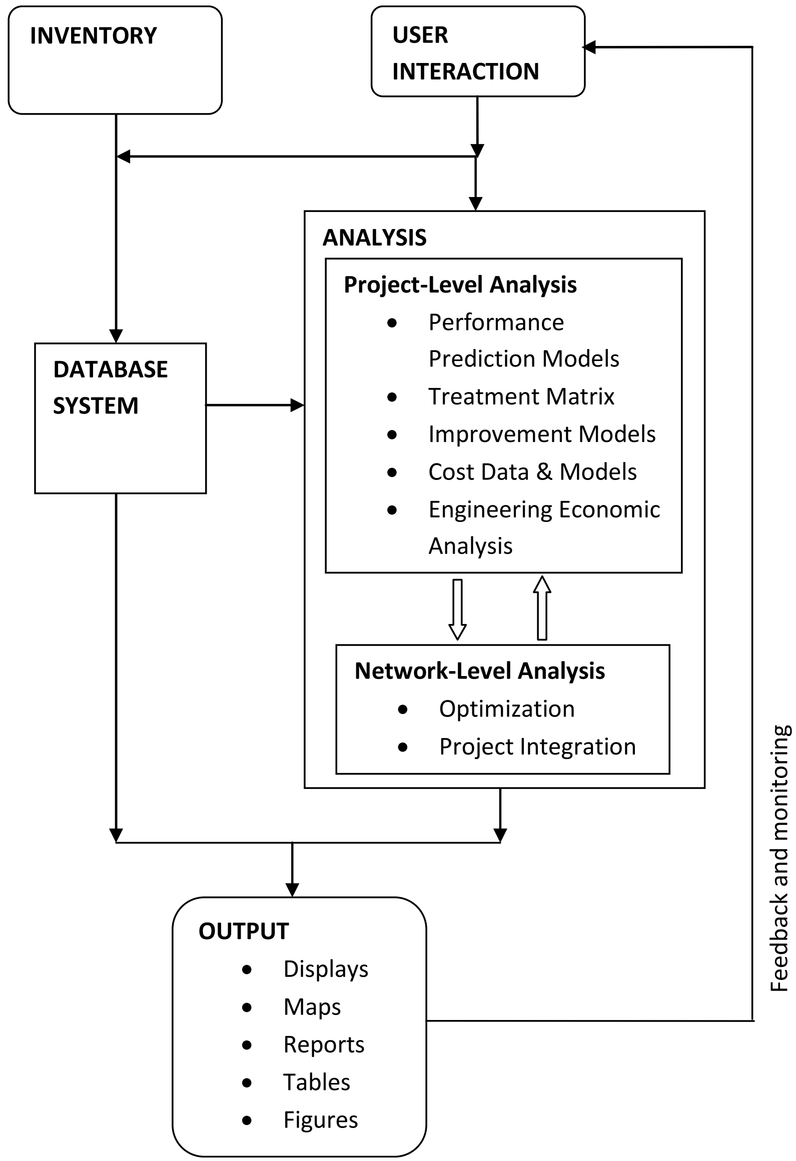
- Introduction
- Objectives
- Deterioration Models
- Project-Level Analysis
- Network-Level Analysis
- Contributions
- Conclusions and Recommendations

INTRODUCTION

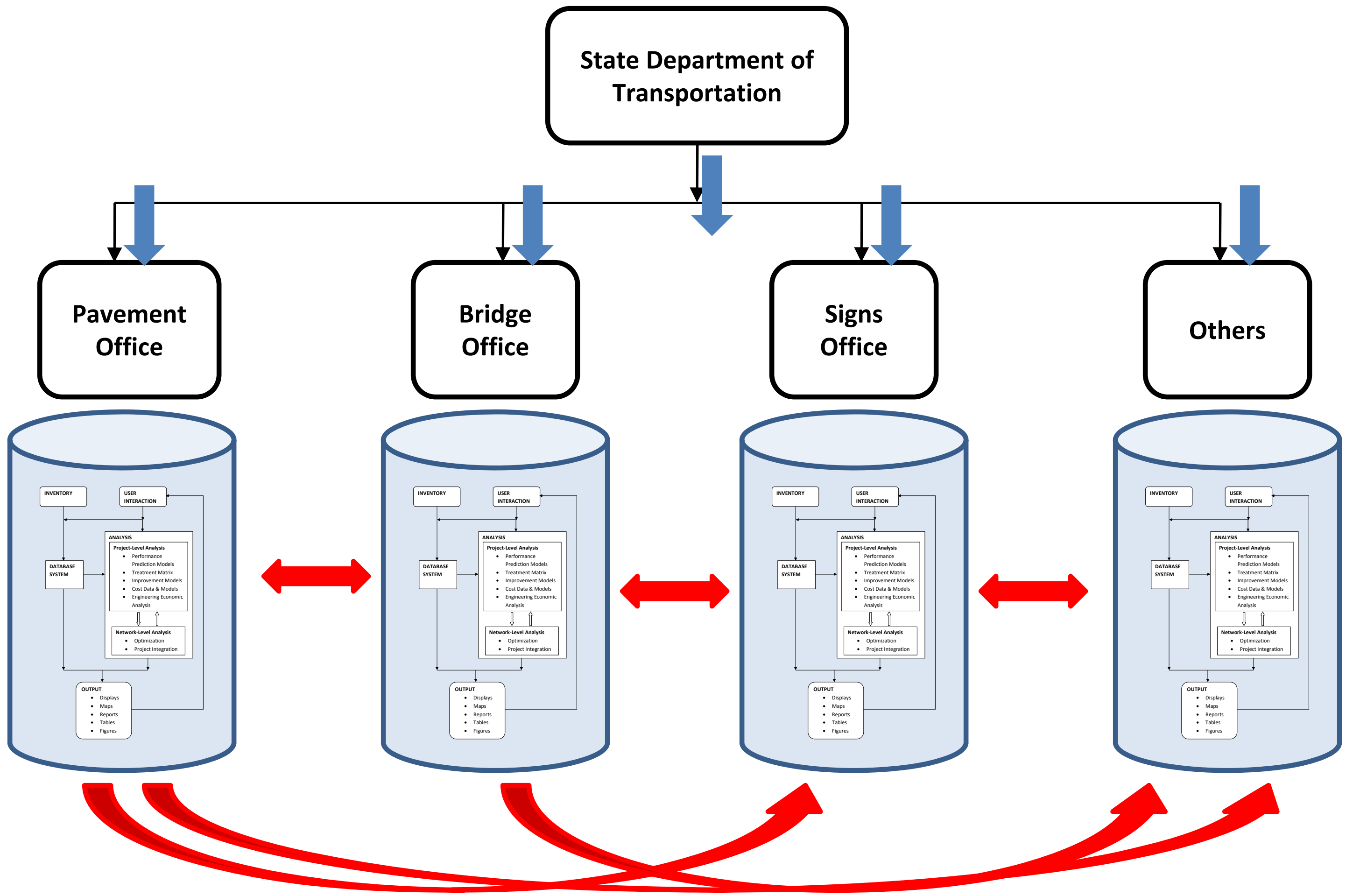
- Transportation infrastructure assets :
  roads, bridges, culverts, tunnels, traffic control systems, and roadside appurtenances such as guardrails, lighting systems, and supports and structures for signs, signals and luminaries.

- An asset management system can be defined as an "integrated set of processes and systems to achieve optimal and cost-effective use of assets throughout their service life, including identification of the need for an asset, acquisition enhancement of assets, utilization-operation, maintenance and improvement, and disposal of assets." (Midwest Regional University Transportation Center , 2005)

INTRODUCTION



INTRODUCTION



INTRODUCTION

- Impacts of stovepipe/ silo approach
  - Inefficient use of decreasing funds
  - Lack of coordination of work programs
  - Increased traffic impacts to road users
- A holistic, overall approach to funds allocation is needed

Research Objectives

- Develop a overall framework such that decision-making and allocation of funds can be performed within each asset class AND across competing asset classes.

- Develop methodologies to integrate projects across classes to minimize impacts to road users.

INTRODUCTION

- The performance prediction model shows the relationship between an indicator of performance e.g. condition, to a set of explanatory variables such as cumulative traffic load, or age.

- where no maintenance actions are performed on a facility, condition decreases over time and the resulting performance profile is called the deterioration curve.

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INTRODUCTION

- In the US bridge methodologies are standardized due to *PONTIS*^{TM}, which has now been adopted by 48 states and foreign jurisdictions

- For bridges current state-of-practice is to model deterioration as the Markov process

$$\{X_n, \quad n = 0, 1, 2, \ldots\}$$

$$P\{X_{n+1} = i_{n+1} \mid X_0 = i_0, \ldots, X_n = i_n\} = P\{X_{n+1} = i_{n+1} \mid X_n = i_n\}$$

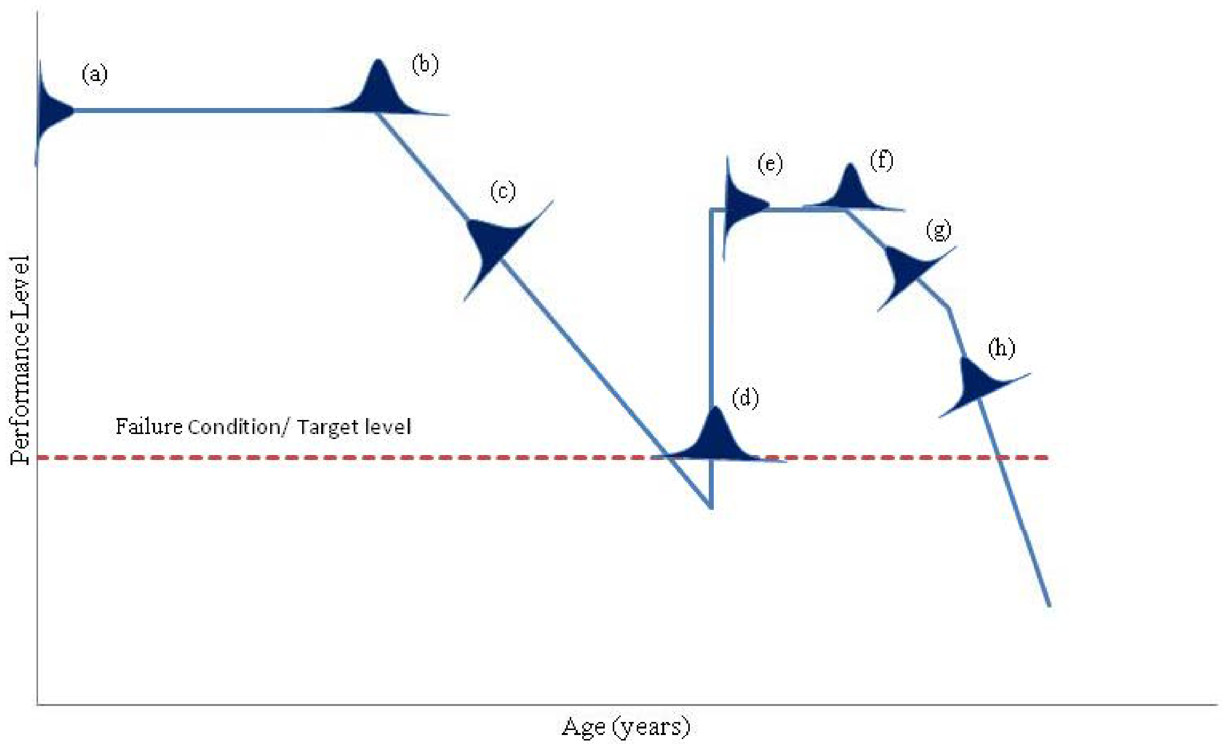
INTRODUCTION

- It has been suggested that the weakness of Markovian models can be overcome by applying reliability-based methods
- Reliability methods are stochastic and capable of modeling the propagation of deterioration effects throughout the whole life process of a facility

Research Objectives

- Develop reliability-based models for deterioration of pavements, bridges, and culverts.
- Performance measures in use are predominantly based on condition which is itself a quasi-subjective measure.
- Feasible performance measures based on intrinsic structural properties will be investigated and applied in the deterioration models.

BRIDGE DETERIORATION MODELS



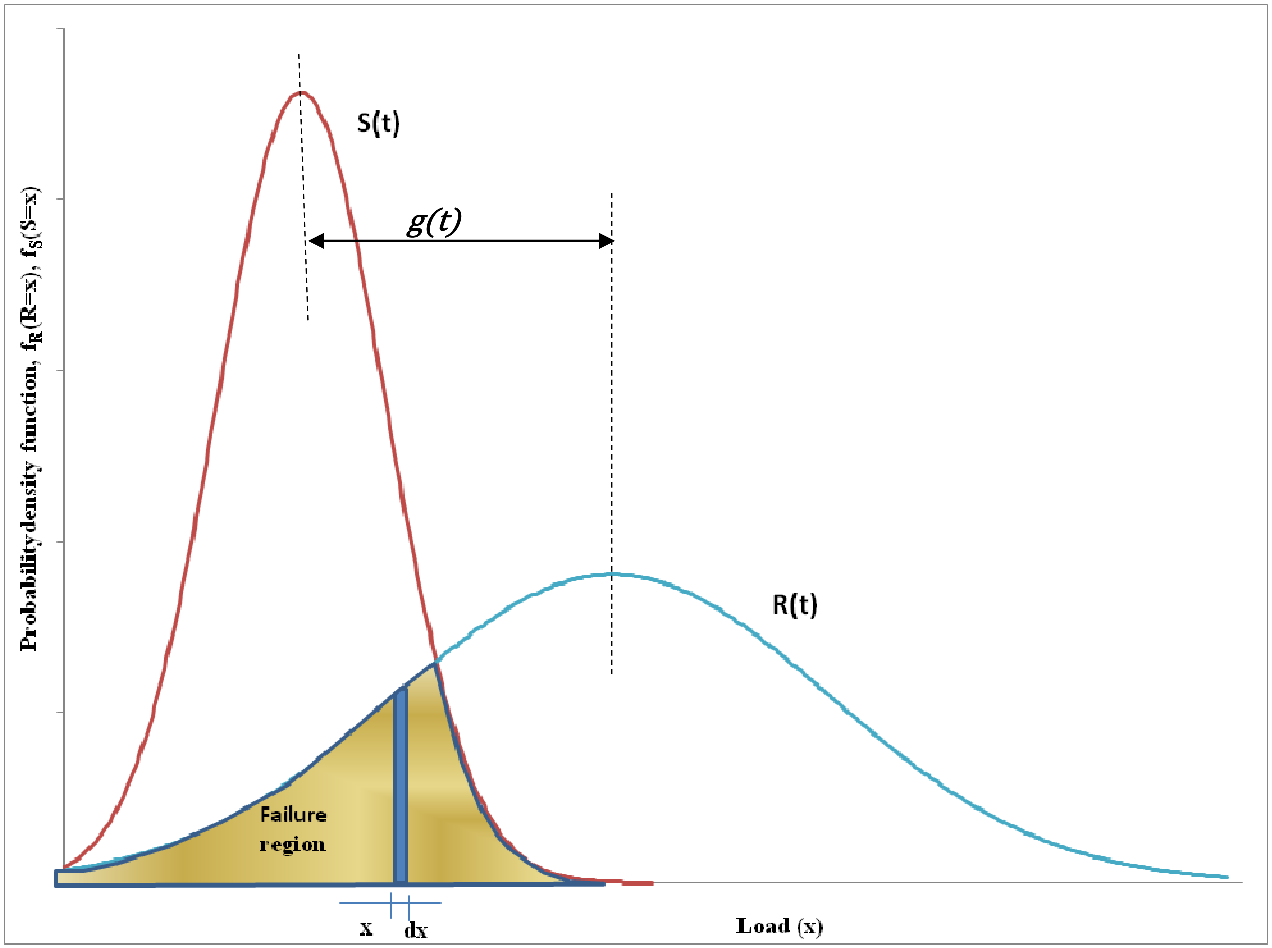
- The whole life process model, a series of random variables (Frangopol et al 2001)

- (a) Initial performance
- (b) Time to damage initiation
- (c) Performance deterioration rate without maintenance
- (d) Time of first major maintenance, repair or rehabilitation
- (e) Improvement in condition level due to major maintenance activity
- (f) Time of damage initiation after major maintenance has been performed.
- (g) Performance deterioration rate after major maintenance has been performed
- (h) The second (accelerated) deterioration rate as the facility approaches failure.

Reliability Index

- The measure of bridge performance in this model is the structural reliability index.
- Advantages over current condition-based methods:
  - is based on a quantifiable intrinsic structural property of a structure such as those used in the formal design of structures
  - “the probability that the structure under consideration has proper performance throughout its lifetime.” (Sorenson, 2004)
  - provides the means to capture the propagation of uncertainty of the structure during the whole life process.
  - a measure of the safety of the structure

Reliability Index



Using bridge operating rating, margin of safety,

$$g(t) = R(t) - S(t)$$

Failure criterion,

$$g(t) \leq 0$$

Probability of failure,

$$P_F = P[(g(t) \leq 0]$$

Summation of distributions,

$$g(t) \sim \mathrm{N}\left(\mu_R - \mu_S, \sqrt{\sigma_R^2 + \sigma_S^2}\right)$$

By definition,

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}$$

- Also the area of the failure region is the probability of failure

$$P_F = P(R \le S)$$

$$= \int_{-\infty}^{\infty} P(R \le x).P(x \le S \le x + dx)dx$$

$$= \int_{-\infty}^{\infty} F_R(x).f_s(x)dx$$

- By definition

$$P_F = \Phi(-\beta)$$

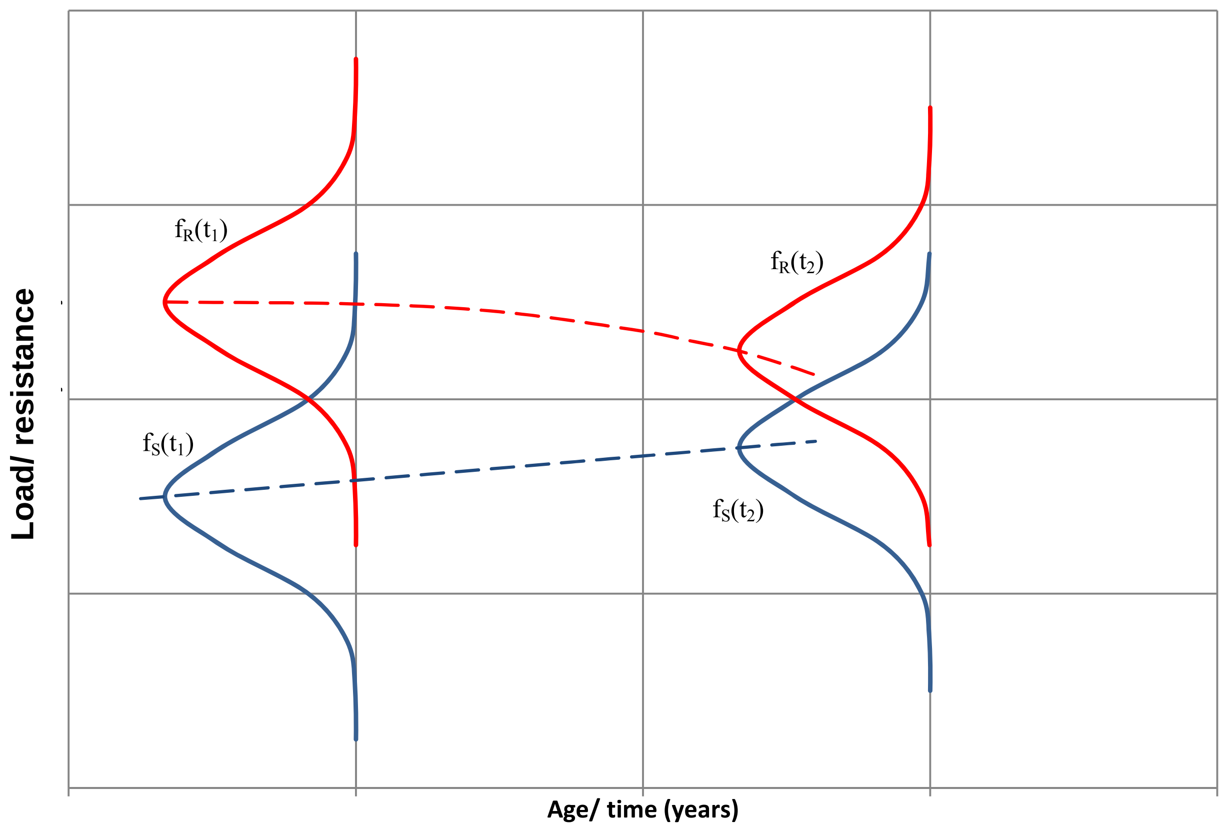
and therefore

$$\beta = -\Phi^{-1}(P_F)$$

Variation of Reliability Index Over Time

- Resistance
  - linear, parabolic, and square root functional forms (Mori and Nonaka 2000)
  - gamma process for monotonic temporal accumulation of degradation of the resistance (Pandey et al 2005)
- Load
  - Linear function (Moses 2001)

Temporal Variation of Reliability Index



Variation of Resistance

Cumulative loss of resistance at time *t*

$$X(t) \sim \text{Gamma}\left(x \mid \lambda(t), \beta\right)$$

Resistance at time t

$$R(t) = R(0) - X(t)$$

Solution by first order reliability methods (FORM)

Probability mass function of gamma distribution

$$f_{X(t)}(x) = \frac{\beta^{\lambda(t)}}{\Gamma[\lambda(t)]} x^{\lambda(t)-1} e^{-\beta x}$$

With mean and standard deviation

$$\mu_{X(t)} = \frac{\lambda(t)}{\beta} \qquad \sigma_{X(t)} = \sqrt{\frac{\lambda(t)}{\beta^2}}$$

Variation of Truck Load

- Moses (2001)
  - 0.3% annual increment
  - Therefore load in truck data year versus original year

$$S_{data} = S_O[1 + 0.3\% \, (Y_{data} - Y_O)]$$

$$S_O = \frac{S_{data}}{1 + 0.3\% \, (Y_{data} - Y_O)}$$

  - Load in current year versus original

$$S_{current} = S_O[1 + 0.3\% \, (Y_{current} - Y_O)]$$

$$S_{current} = S_{data'} \frac{1 + 0.3\% \, (Y_{current} - Y_O)}{1 + 0.3\% \, (Y_{data} - Y_O)}$$

Expected Load in Year *t*

- For a bridge with *m* lanes and proportion of trucks in traffic stream in lane *i* , $ADTT_i$,
- $$S_{total}(t) = S_{lane1}(t) + S_{lane2}(t) * ADTT_2 + \ldots + S_{lane\,m}(t) * ADTT_m$$

For $ADTT_i = ADTT$, for all $i = 1$ *to m*

$$S_{total}(t) = S(t) + (m-1).S(t).ADTT$$

- The above over a horizon yields reliability profile
- Next step is to fit milestones to distributions

LIKELIHOOD-BASED METHODS

- Likelihood methods provide a formal tool to fit known statistical distribution models to historical data

- The likelihood function by definition is either equal to or proportional to the probability of the data.

- The premise of likelihood inference is that model-parameter combinations yielding relatively higher probability represent a better fit to the data.

Reliability (Duration-based) Data

- Exact observations
- Left-censored data
- Right-censored data
- Interval-censored data
- Combinations of data types is called arbitrarily censored data

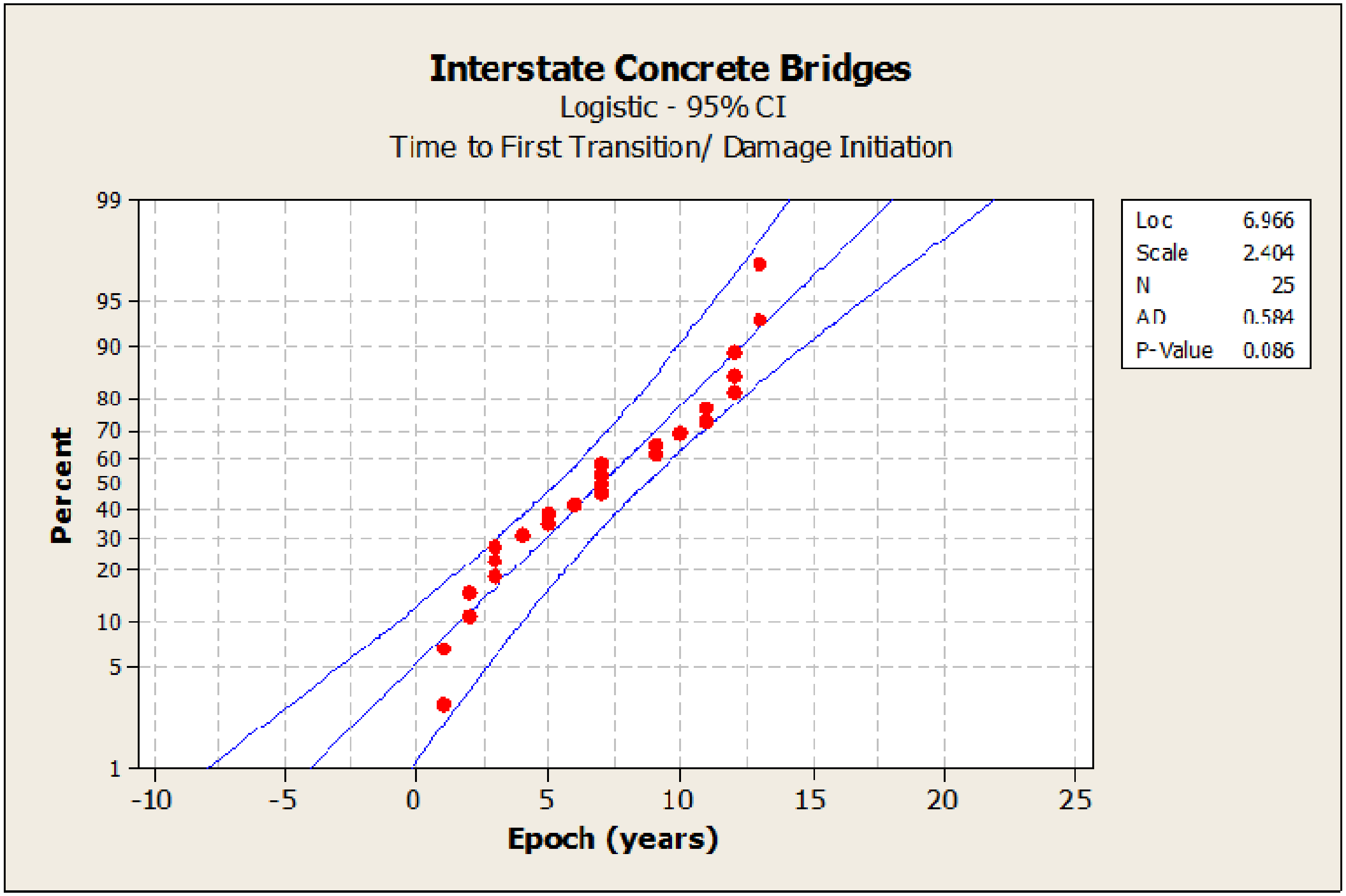
Likelihood Methods

- DeLisle et al (2003) modeled pavement condition failure times. Exact and right censored observations only
- Sobanjo et al (2009) modeled failure times of bridge components' condition. Exact and right censored data only
- Proposed whole life deterioration methodology synthesizes exact observations

Data Collection

- Interstate facilities
  - Concrete bridges: 291 records
  - Culverts: 204 records
  - Prestressed bridges: 801 records
  - Steel bridges: 127 records
- Non-Interstate facilities
  - Concrete bridges: 2,067 records
  - Culverts: 1,088 records
  - Prestressed bridges: 1,878 records
  - Steel bridges: 506 records

Reliability Index Profile - Probability Plotting



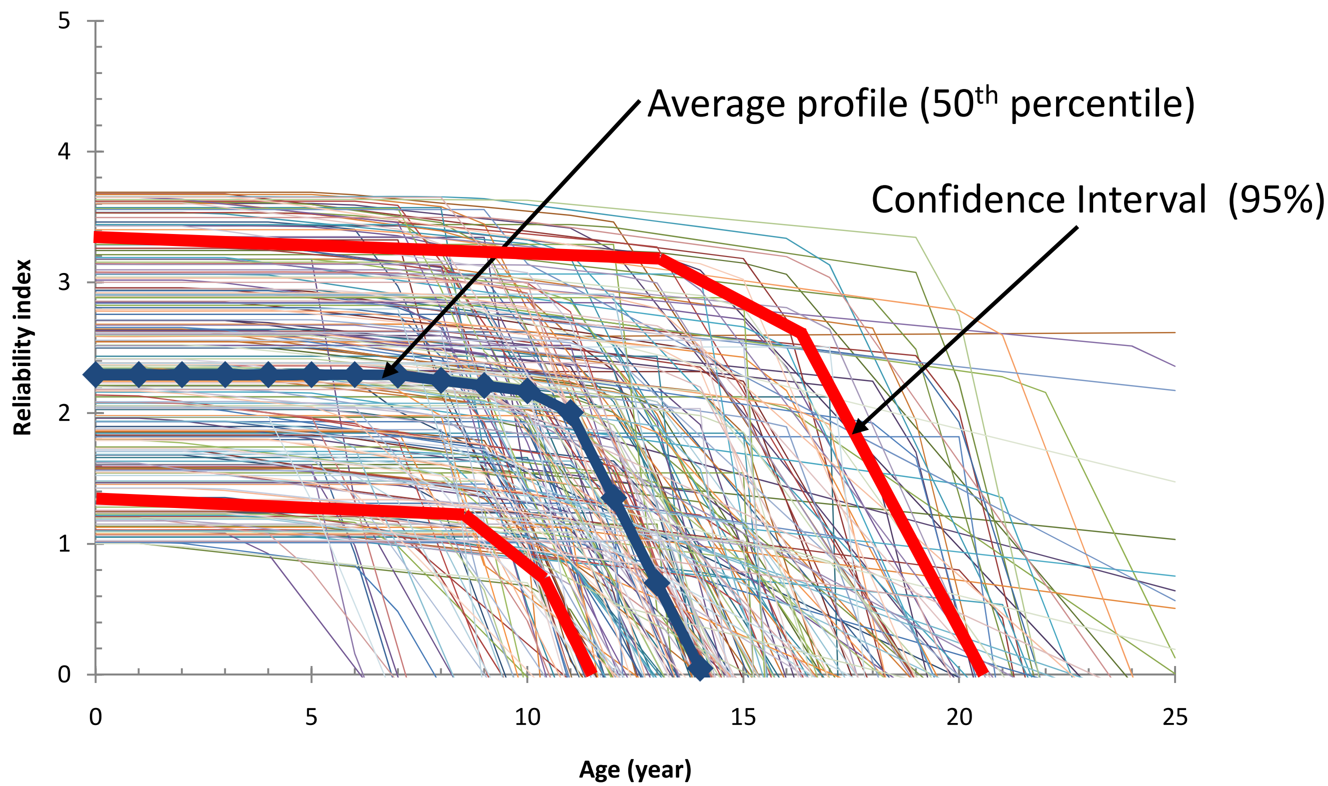
Reliability Index Parameters – Sample Results

Family	Rate of deterioration (kips/ year)	Random Variable	Distribution Type	Anderson-Darling Value	Sample Size	Distribution Parameters		
Interstate Concrete	1.8539	β_0	uniform	-	276	a = 1.0	b = 3.7	
		t_{I1}	Weibull	0.609	25	σ = 1.809	m = 7.855	
		α_1	uniform		25	a = 0.03	b = 0.05	
		t_{I2}	lognormal	0.327	8	Θ = 2.274	m = 0.364	
		α_2	triangular	-	8	a = 0.1	b = 0.1	c = 1.3
Non Interstate Concrete	2.2754	β_0	triangular	-	1453	a = 0	b = 3.85	c = 1.5
		t_{I1}	na	na	na	na	na	na
		α_1	triangular	-	1453	a = 0.0444	b = 0.0551	c = 0.0600
		t_{I2}	na	na	na	na	na	na
		α_2	na	na	na	na	na	na

Notes:

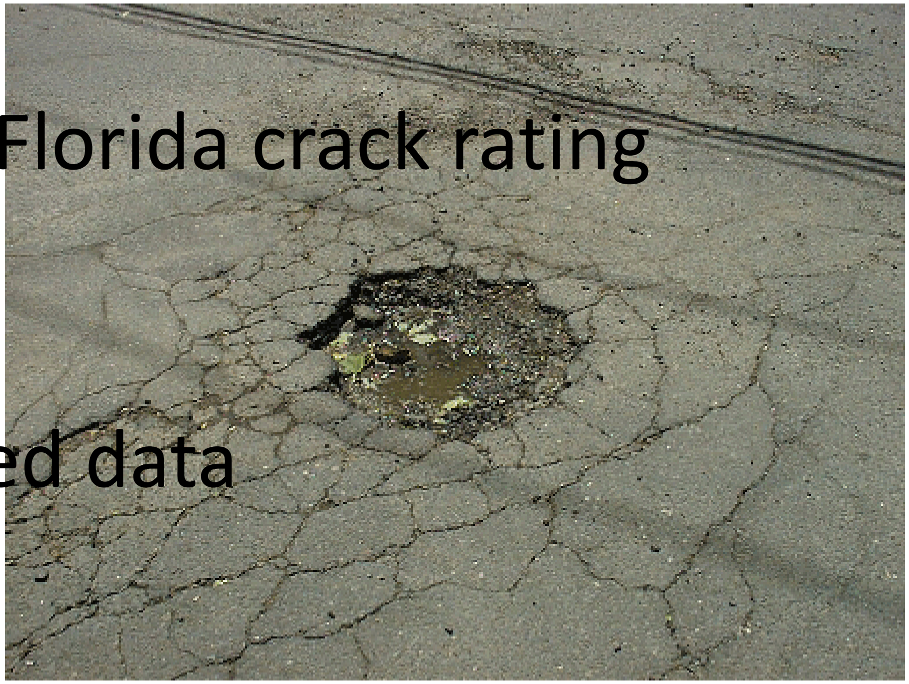
a denotes lower bound of the distribution
b denotes upper bound of the distribution
c denotes mode of the distribution
Θ denotes location parameter of the distribution
m denotes scale parameter of the distribution
σ denotes shape parameter of the distribution
[illegible] denotes mean of the distribution
SD denotes standard deviation of the distribution
na denotes "not applicable". In other words this property was not observed in the data for that family of bridges and therefore could not be analyzed.

Monte Carlo Simulation – Non Interstate Concrete Bridge

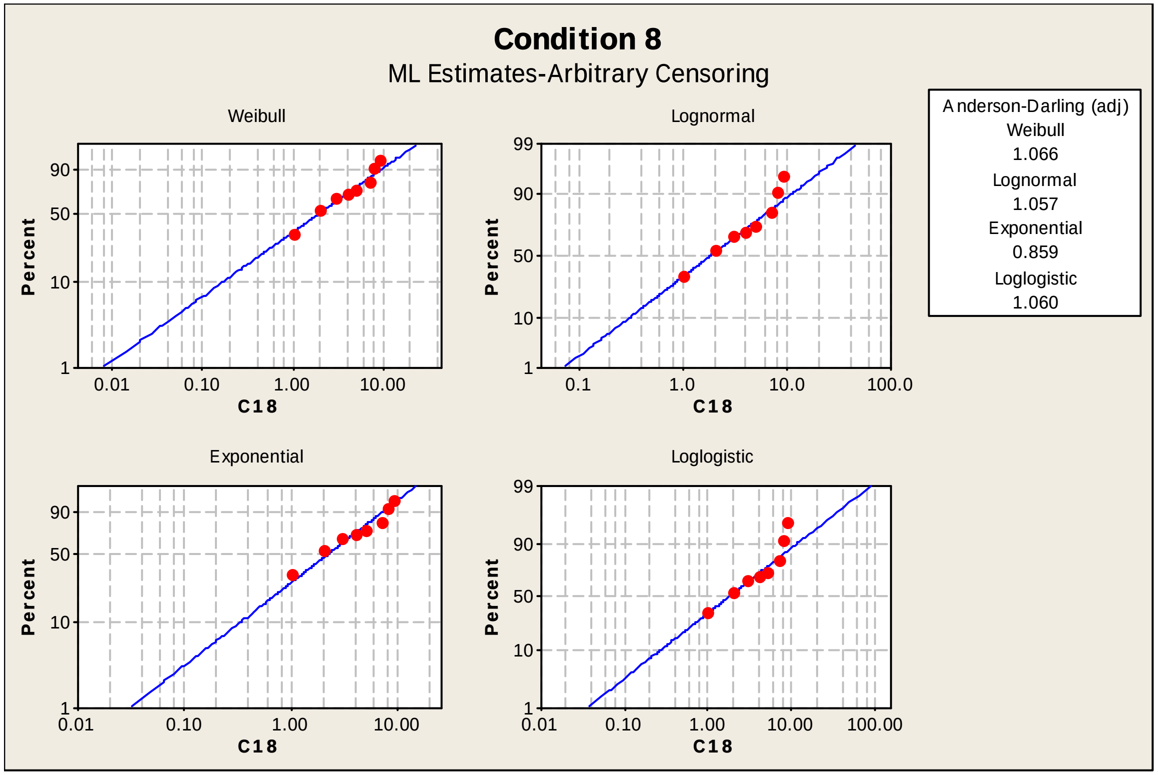


PAVEMENT DETERIORATION MODELS

- This reliability model is based on sojourn times i.e. the time a facility spends in a given performance state before degrading to a lower performance state
- Performance measure: Florida crack rating (condition)
- Data: arbitrarily censored data



Pavement Condition Sojourn Times - Probability Plotting

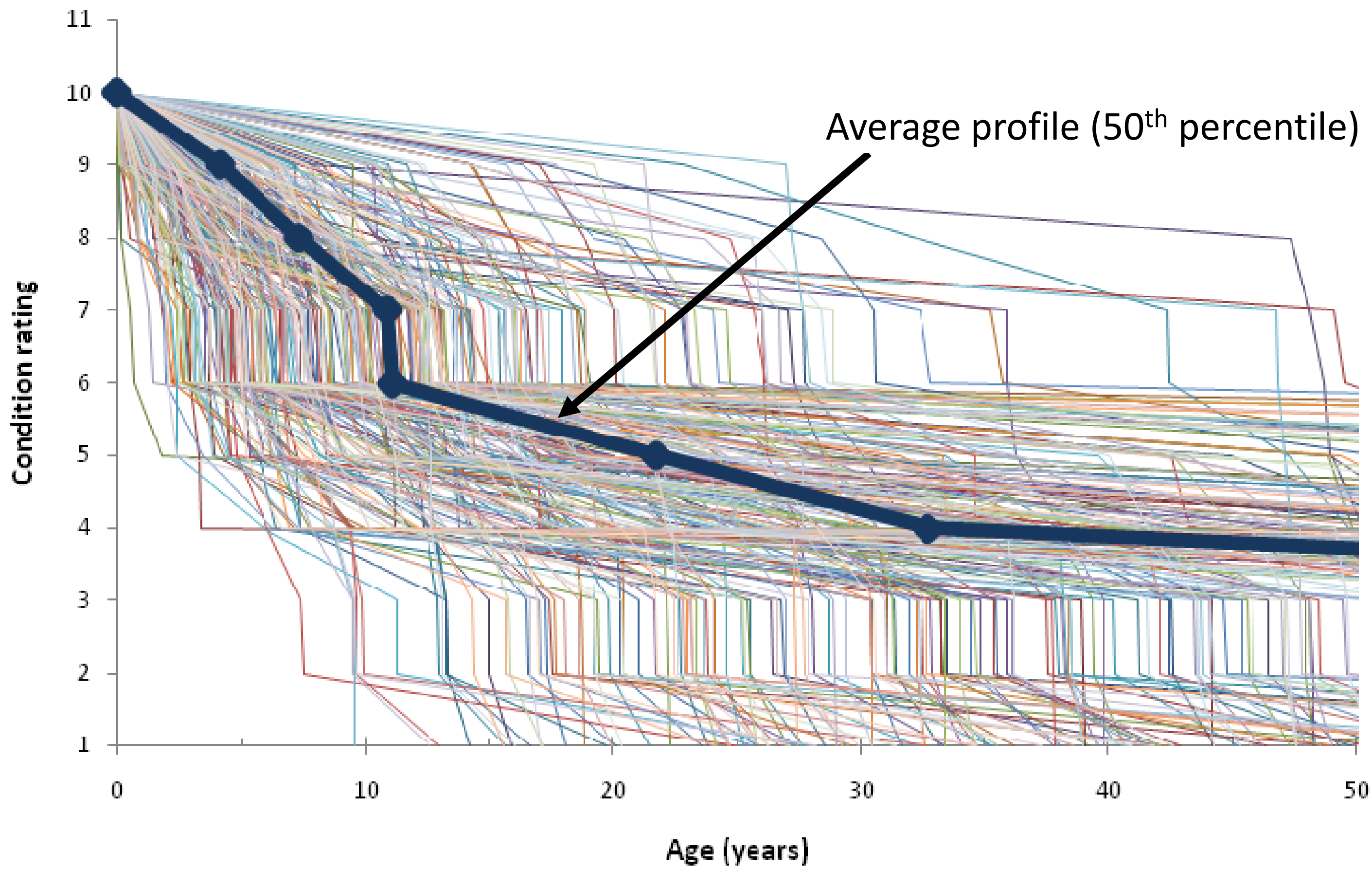


Probability plots for candidate distributions for sojourn time of non interstate asphalt pavement in Condition State 8.

Pavement Sojourn Time Parameters

Pavement Type	Condition State	Distribution Type	Adjusted Anderson-Darling Value	Distribution Parameters
Interstate Asphalt	10	Weibull	0.564	Shape = 1.2914, Scale = 3.2336
	9	Weibull	0.708	Shape = 1.1927, Scale = 2.6825
	8	Lognormal	1.668	Location = 0.3363, Scale = 1.2975
	7	Weibull	12.807	Shape = 0.7535, Scale = 5.0459
	6	Weibull	7.757	Shape = 0.8614, Scale = 3.1269
	5	Weibull	13.907	Scale = 5.6558, Shape = 0.8134
	4	Exponential	21.804	Rate = 0.1233
	3	Weibull	27.503	Shape = 0.8134, Scale = 5.6558
	2	Insufficient data	-	Insufficient data
	1	Weibull	11.056	Shape = 2.49704, Scale = 4.3650
Non-Interstate Asphalt	10	Weibull	0.889	Shape = 1.0036, Scale = 4.0907
	9	Weibull	0.988	Shape = 0.9920, Scale = 3.1393
	8	Lognormal	1.039	Location = 0.6638, Scale = 1.0998
	7	Exponential	0.605	Rate = 0.1992
	6	Lognormal	10.463	Location = 1.2962, Scale = 1.4710
	5	Weibull	34.034	Shape = 0.8020, Scale = 9.9325
	4	Lognormal	47.660	Location = 2.1487, Scale = 2.0042
	3	Exponential	55.083	Rate = 0.0477
	2	Weibull	13.334	Shape = 0.5768, Scale = 5.6017
	1	Loglogistic	55.547	Location = 3.6136, Scale = 2.0150

Monte Carlo Simulation – Non Interstate Asphalt Pavement



Culvert Sojourn Time Model

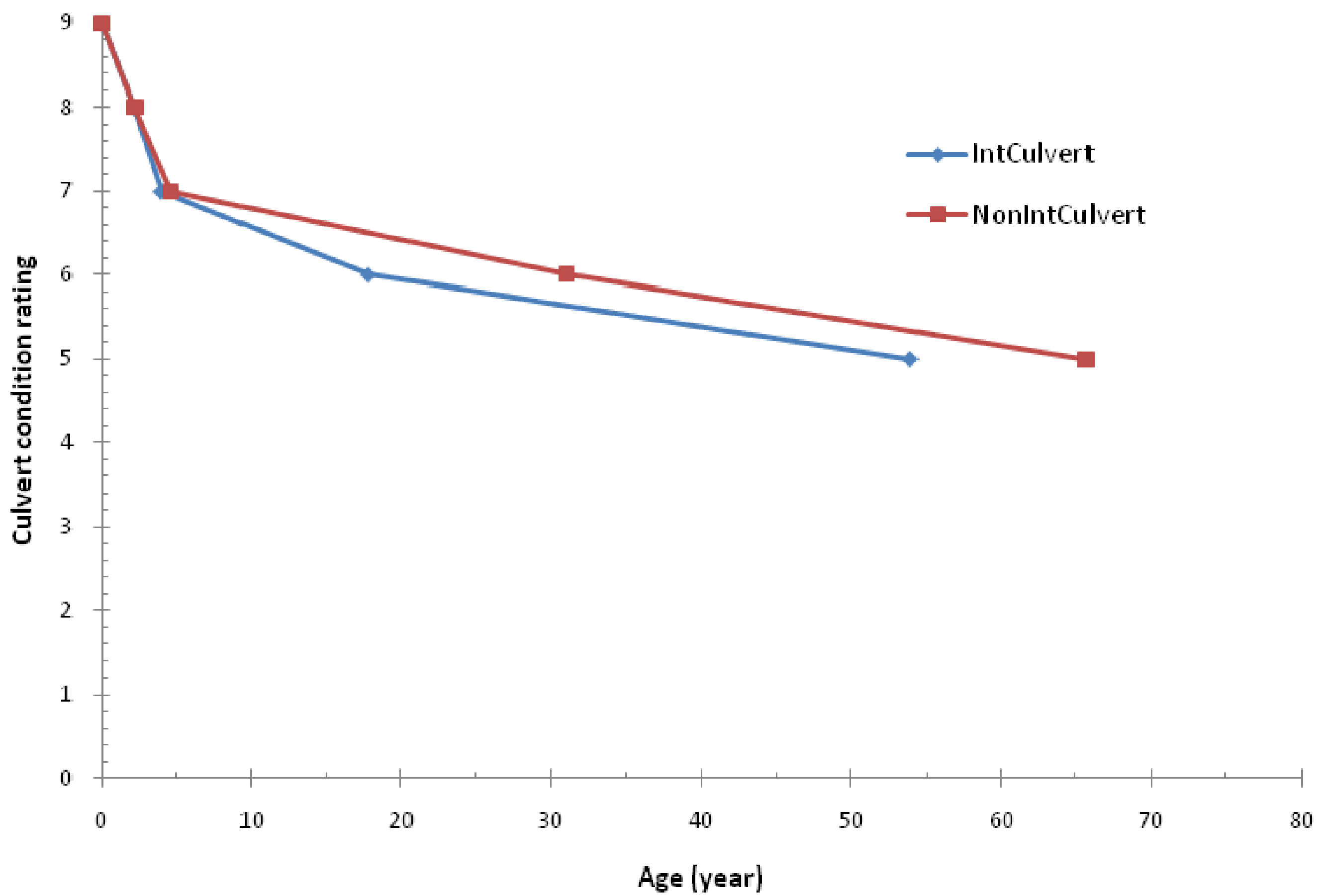
- An alternate likelihood-based Culvert deterioration model using Culvert condition sojourn times (NBI Item 62 – Culvert rating) was developed.

- Arbitrarily censored data for Florida interstate and non-interstate culverts

Culvert Sojourn Time Models

Pavement Type	Condition State	Distribution Type	Distribution Parameters
Interstate Culverts	9	Weibull	Shape = 0.581 Scale = 1.423
	8	Weibull	Shape = 0.474 Scale = 0.808
	7	Weibull	Shape = 1.061 Scale = 14.13
	6	Weibull	Shape = 1.051 Scale = 36.82
Non Interstate Culverts	9	Weibull	Shape = 0.581 Scale = 1.423
	8	Exponential	Mean = 2.53 Standard deviation = 2.53
	7	Weibull	Shape = 0.639 scale = 18.963
	6	Exponential	Mean = 34.59 Standard deviation = 34.59
	5	Exponential	Mean = 60.48 Standard deviation = 60.48

Culvert Sojourn Time Models



PROJECT-LEVEL ANALYSIS

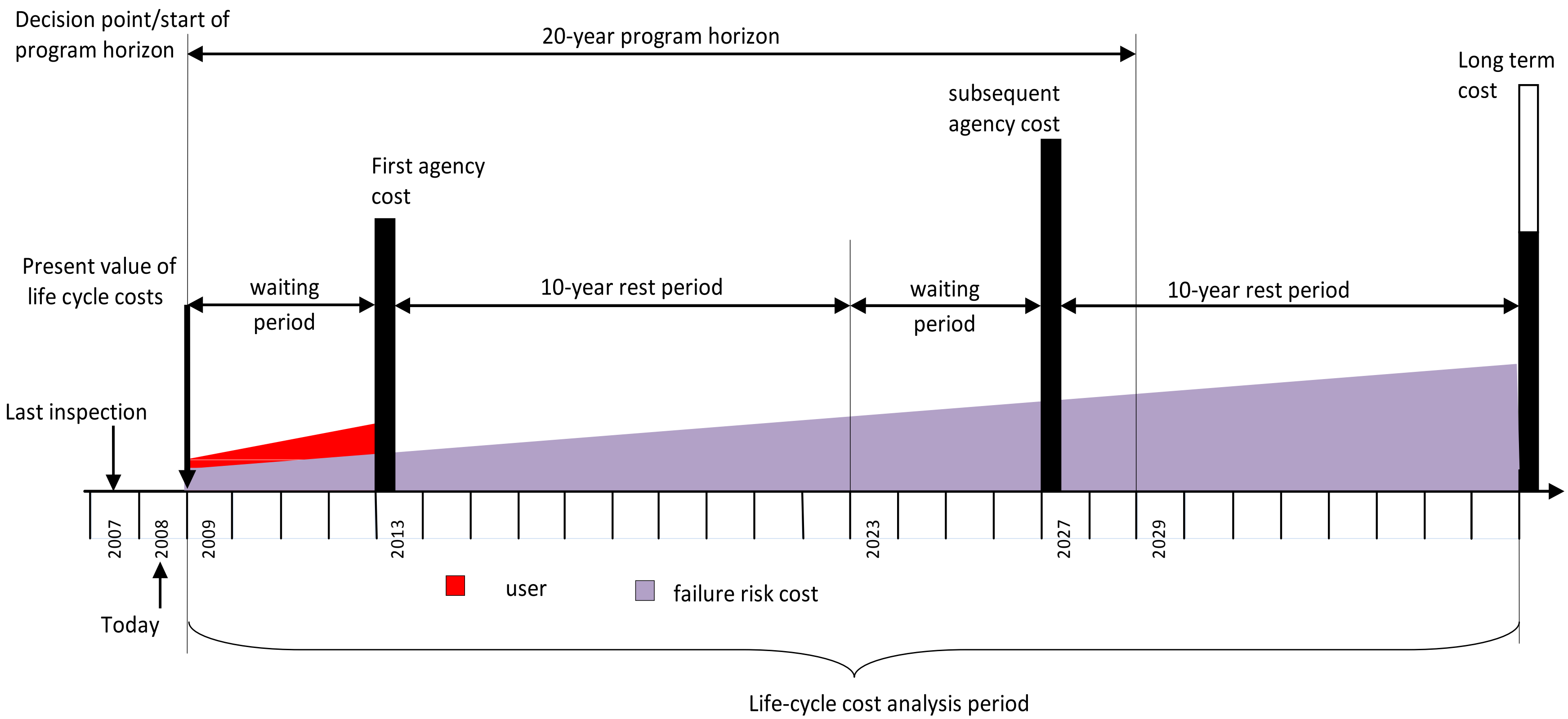
- Treatment matrix: Identifies applicable improvement alternatives based on performance level (Gharaibeh 1997; Miyamoto et al 2001; Wang et al 2002)

- Cost Models/ Data: provides the costs associated with alternative (Gharaibeh 1997; Sobanjo and Thompson 2006)

- Improvement model: determines the new performance level if a specific improvement is implemented (Gharaibeh 1997; Miyamoto et al 2001)

PROJECT-LEVEL ANALYSIS

- Engineering Economic Analysis: Is used to select the cost effective alternative for a facility. The incremental-benefit-cost algorithm was used (Sobanjo and Thompson 2006) .



NETWORK-LEVEL ANALYSIS

- The objective is selecting the strategy that is cost-effective for the entire network of an infrastructure class(s)

- Formulations
  - Individual asset class
  - Multiyear individual asset class
  - Multiyear across all classes (integrated)

- Integrated method is the thrust of this dissertation

Optimization Problem

- The selection of projects for implementation from a candidate list, under budgetary constraints

- This is essentially an optimization problem, called the knapsack problem or integer program.

- Adding multiple objectives and constraints results in the capital budgeting problem.

Integrated Optimization Problem

- Relevant previous research on multiyear integrated formulation
  - Gharaibeh (1997)
  - Sadek et al (2003)

- Other contributions
  - Small and Swisher (1999)
  - Cowe Falls et al (2006)

Optimization Problem – General Formulation

- Objective functions

$$Max \sum_{i=1}^{n} g_i x_i$$

$$Max \sum_{i=1}^{n} p_i x_i$$

- where

g_i = benefit of improvement candidate on facility *i*

p_i = asset service index (performance measure) of facility *i*

n = number of facilities competing for funding

x_i = binary value

Optimization Problem – General Formulation

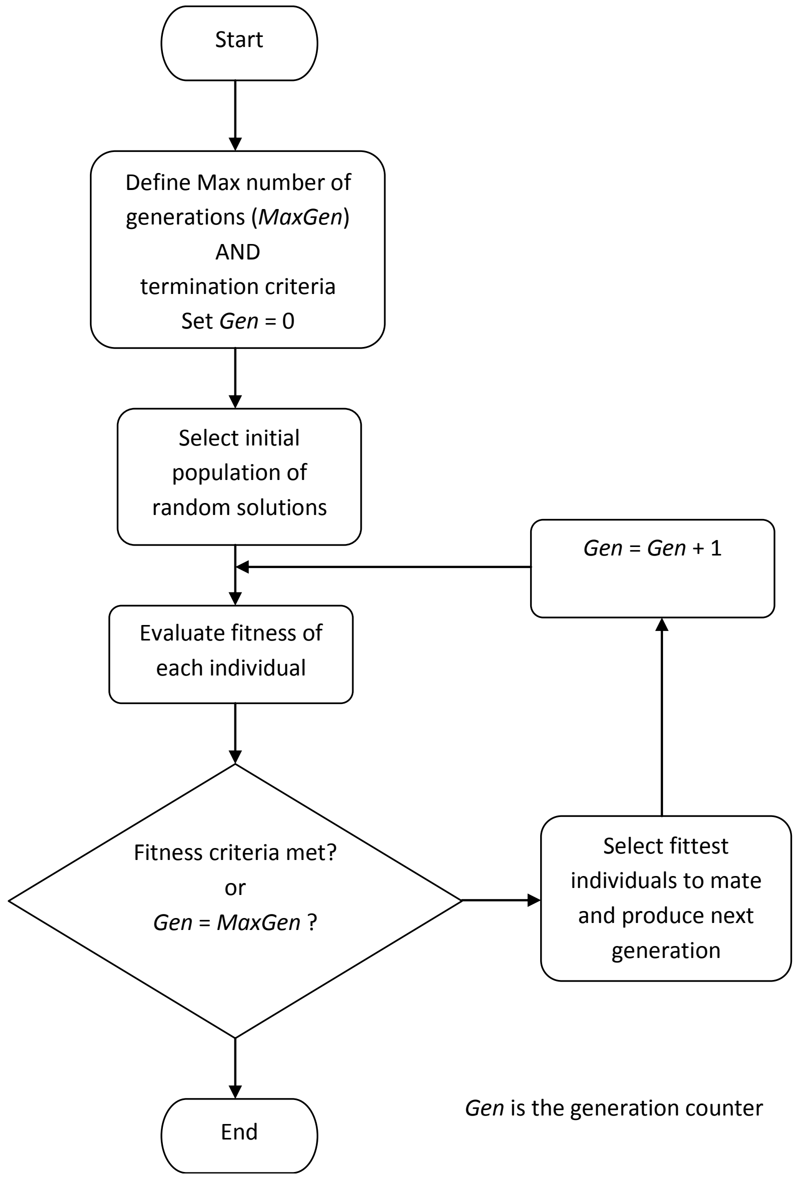
- Subject to budgetary constraint

$$\sum_{i=1}^{n} c_i x_i \leq B_P$$

c_i = cost of improvement for facility *i*
B_P = available budget

- Solution by genetic algorithm (GA)

Genetic Algorithm (GA)



Coding the GA

Pavement ID	Improvement		*M* Candidate Solutions for Generation *k*					
Pavement 1	Improvement 1	....	0	1	1	1	......	0
Pavement 2	Improvement 2	....	0	1	1	0	......	0
Pavement 3	Improvement 3	....	1	1	1	1	......	0
Pavement 4	Improvement 4	....	0	0	1	1	......	0
Pavement 5	Improvement 5	....	1	1	0	1	......	0
Pavement 6	Improvement 6	....	1	1	0	0	......	1
Pavement 7	Improvement 7	....	1	1	0	0	......	1
Pavement 8	Improvement 8	....	0	0	1	0	......	1
Pavement 9	Improvement 9	....	1	0	1	0	......	0
:	:	....	:	:	:	:	......	:
:	:	....	:	:	:	:	......	:
Pavement 4883	Improvement 4883	....	1	0	1	1	......	1

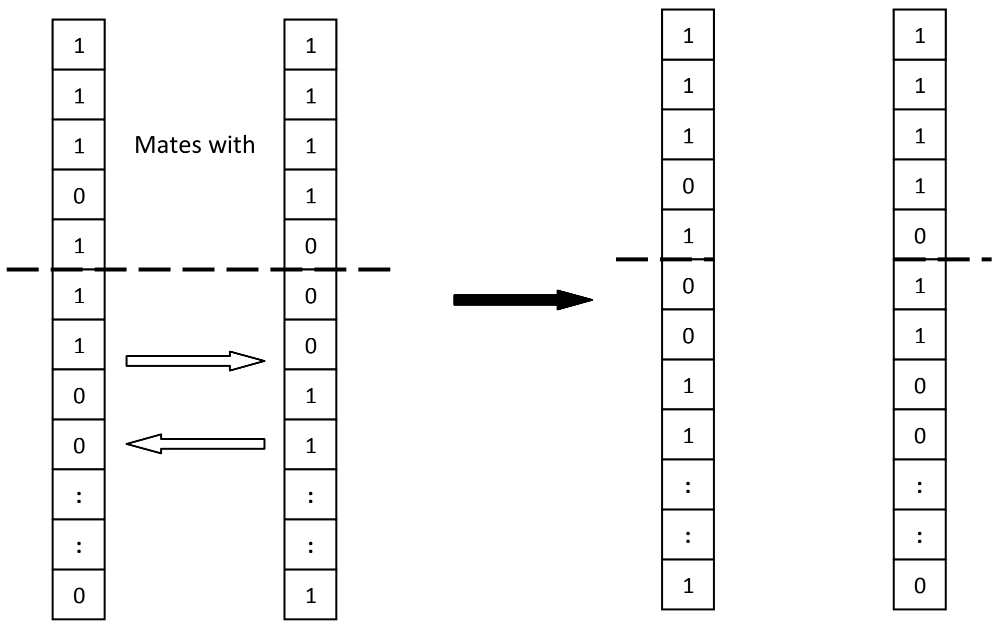
GA Parameters

- Population: A population size of 30 is used in this algorithm.
- Generations: The GA will set up to terminate after 300 generations.
- Fitness Function:
  - objective functions: network benefit, network asset service index network asset service index
  - Rank objective for each candidate. Add two rankings to yield a “combo” ranking. Rank combo rankings The lower the combo ranking value, the higher the multi-objective ranking.
  - Feasible solutions are those in compliance with network budgetary constraint.

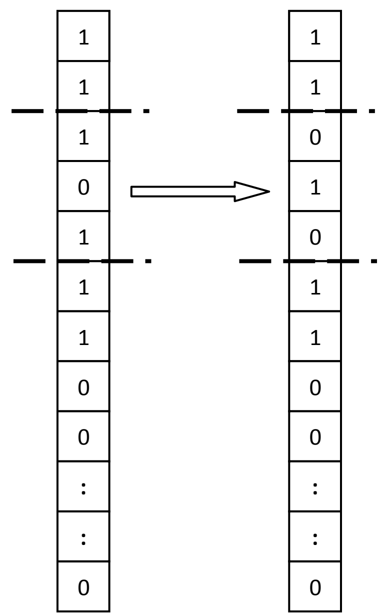
Genetic Operators

- Selection
  - elitist approach: top three percent (3%) of candidates to automatically move into the next generation.
  - Crossover scheme used to mate 85% of candidates
  - Mutation rate of 6%
  - Immigration rate of 6%

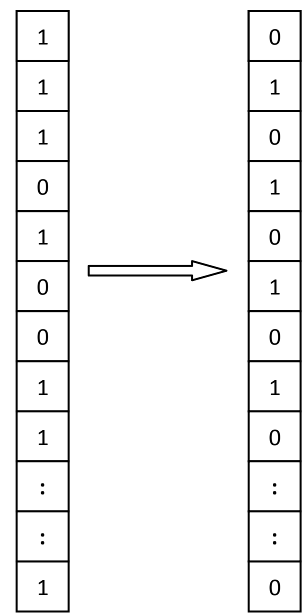
Crossover Operator



Mutation Operators



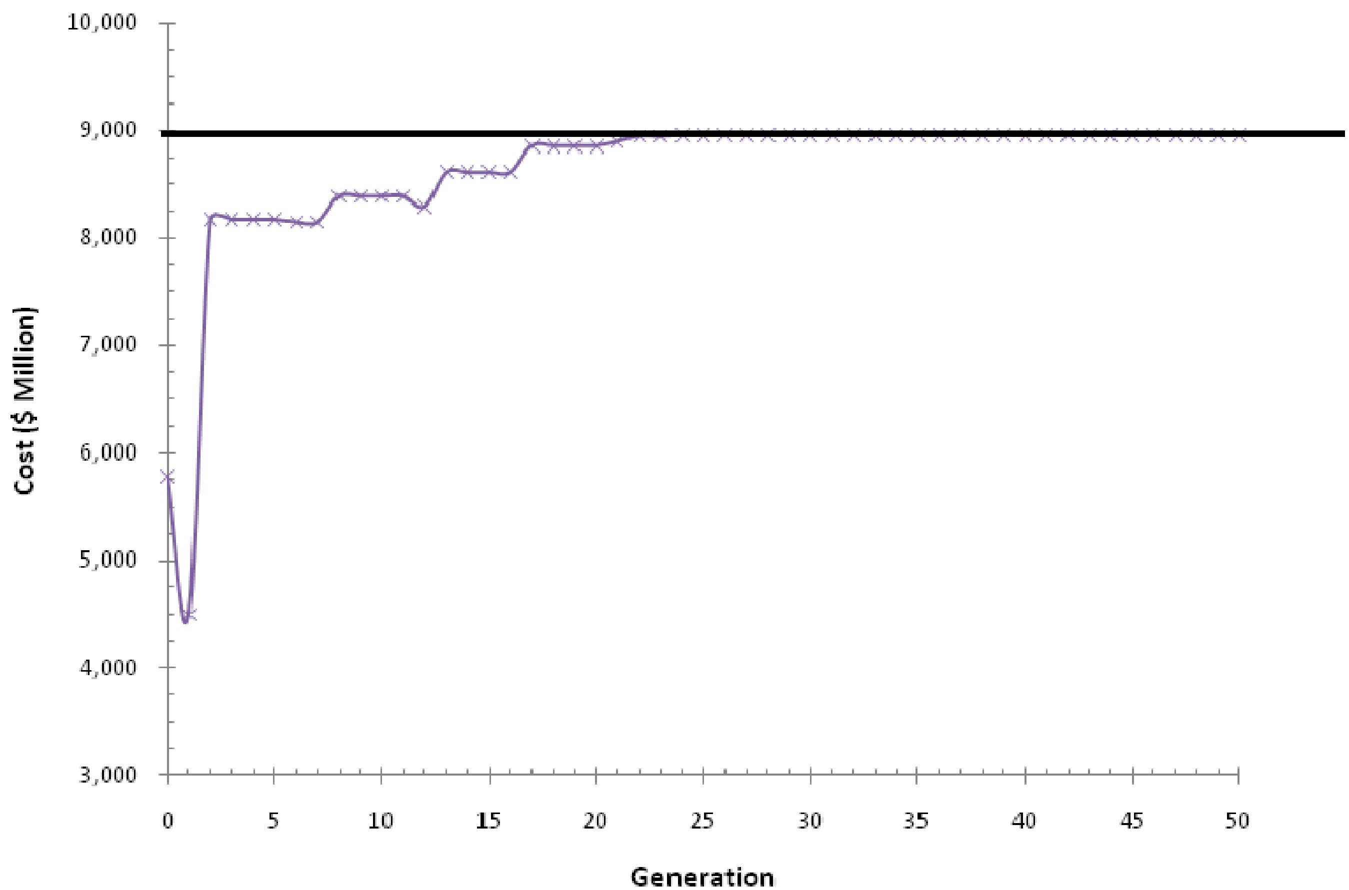
Mutation



Immigrant

Evolutionary curve - cost

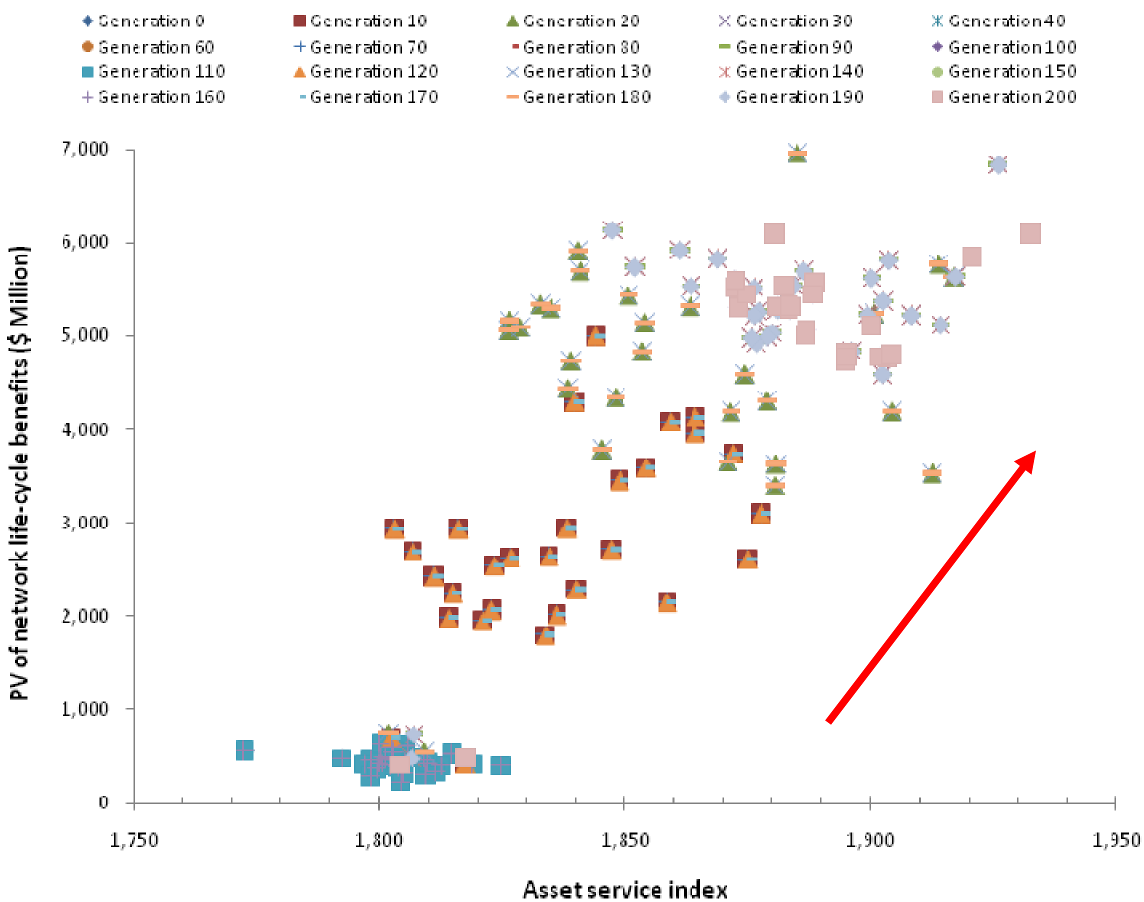
- Sample budgetary constraint of $9 Billion (statewide)



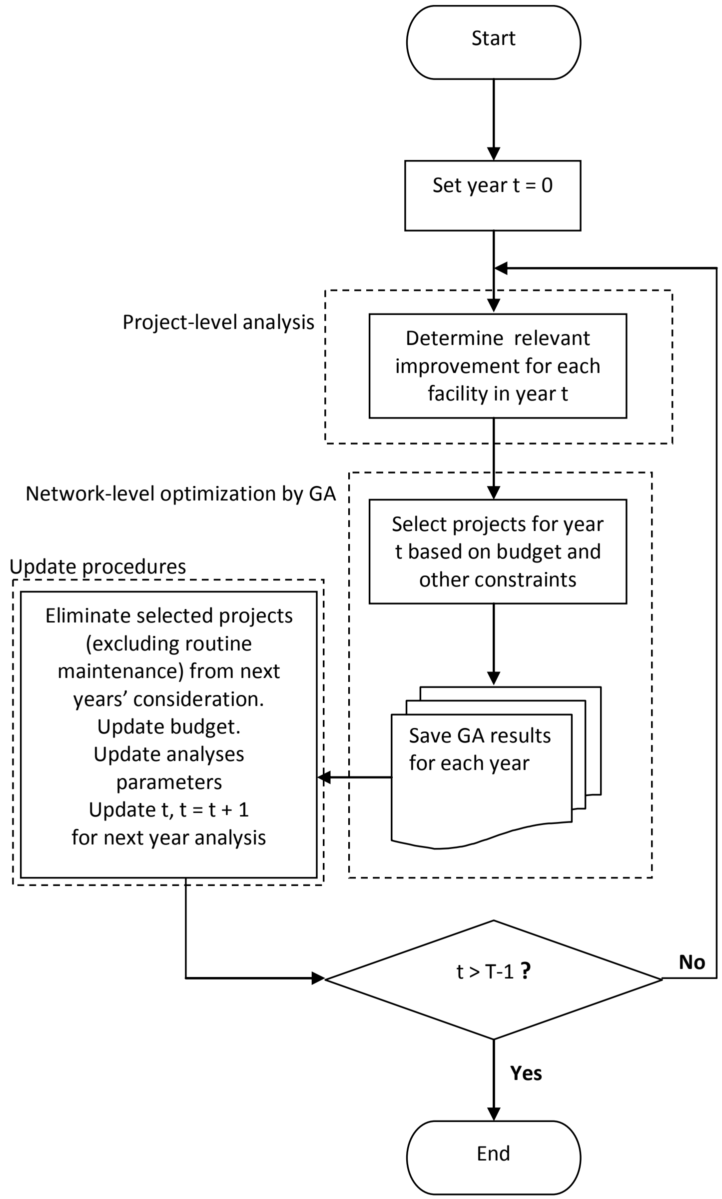
Capital Budgeting Formulation

Parameter	
Network	1,316 pavement sections
Population size	30
Maximum generations	300
Fitness function(s)	- Network ASI (objective function) -Network benefit (objective function) -Network budget (constraint) -System condition requirement (constraints): 70%, condition rating $\geq$ 5
Selection	Elitist 3% Ranking
Crossover rate	85%
Mutations	6%
Immigration rate	6%

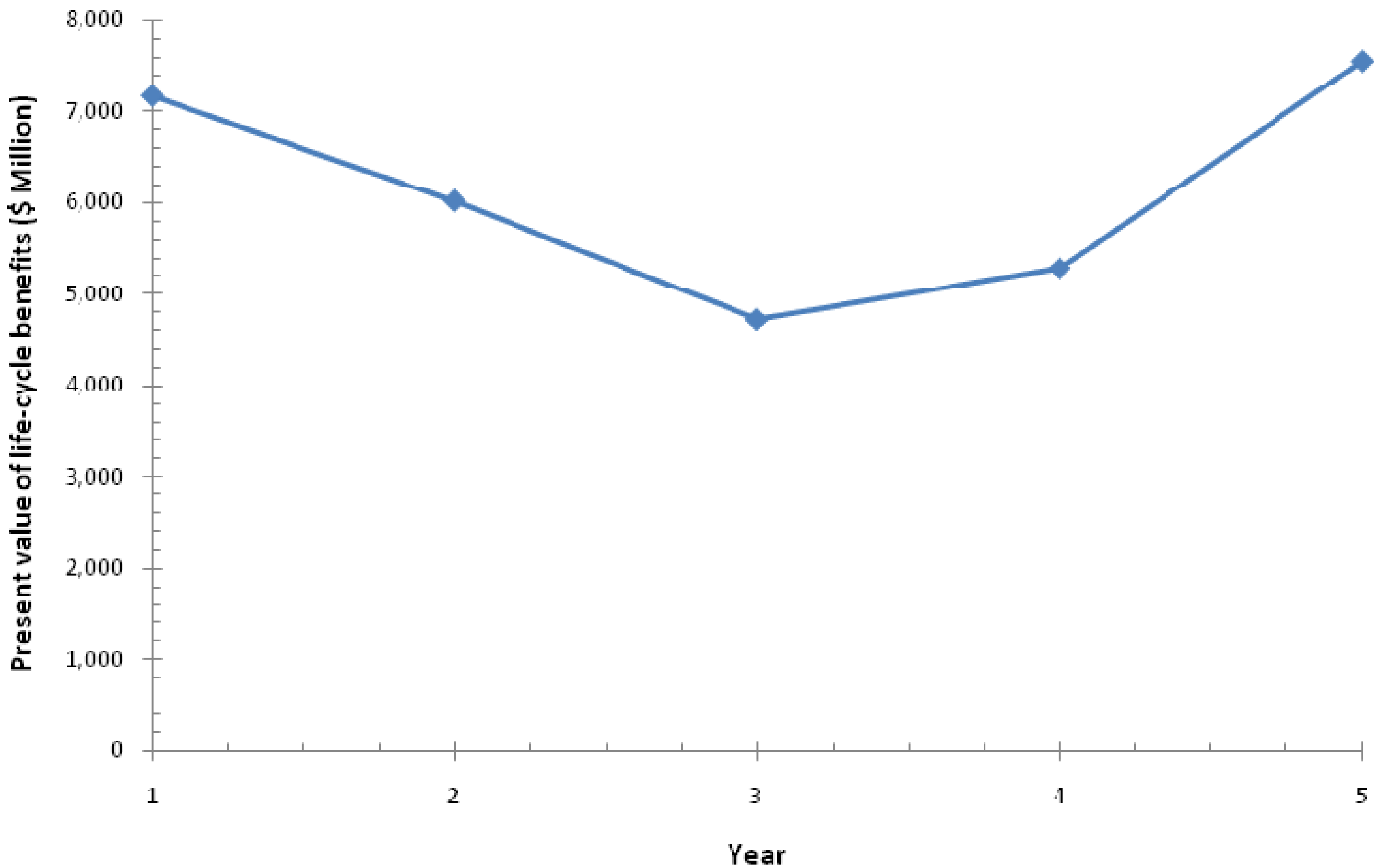
Dominance of solutions



Multiyear Capital Budgeting Problem



Benefits over 5-yr horizon



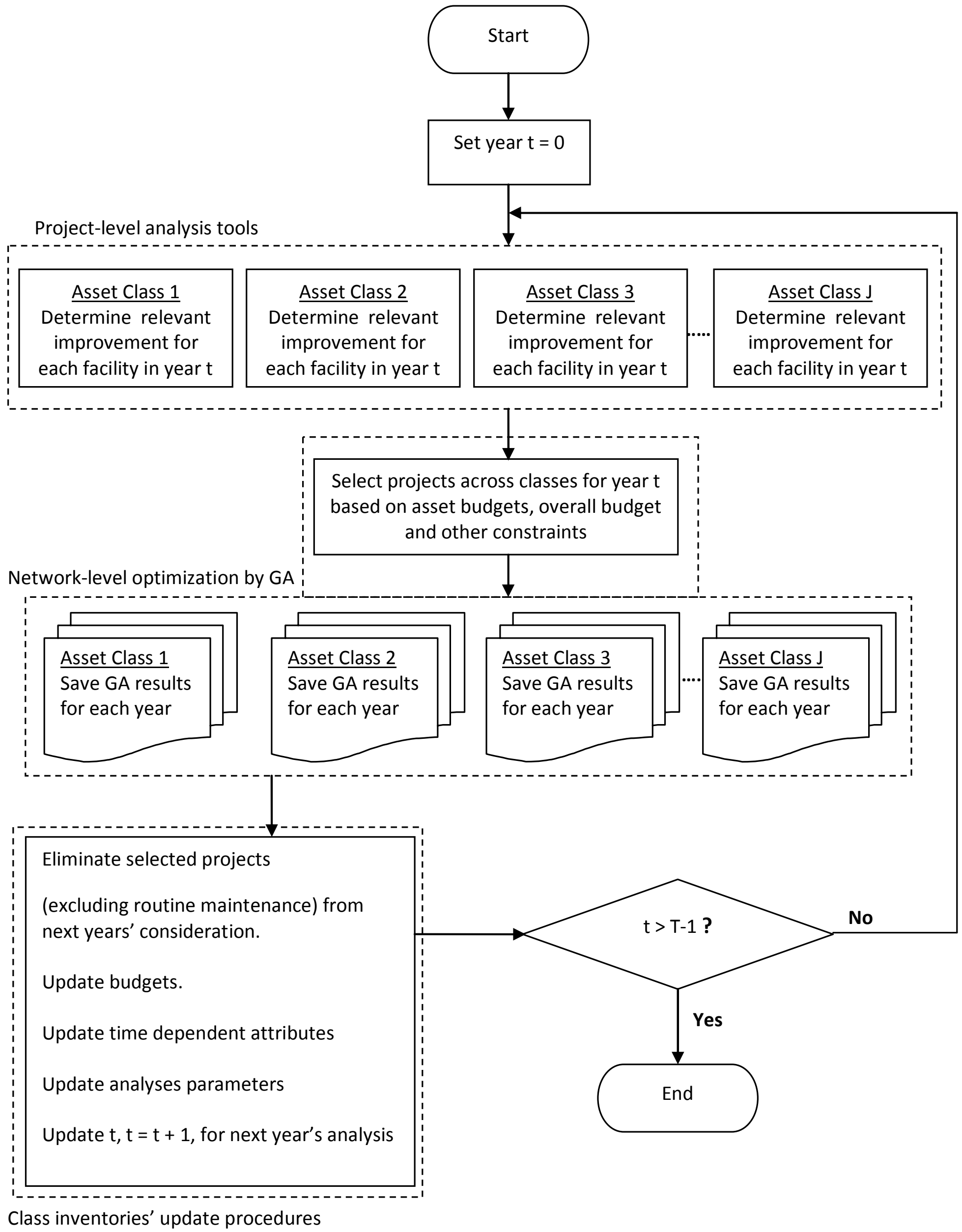
Multiyear Integrated Optimization

Asset Class	**Asset ID**	**Improvement**		***M* Candidate Solutions for Generation *k***					
Pavement	Pavement 1	Pavement Improv 1	………	0	1	1	1	……	0
	Pavement 2	Pavement Improv 2	………	0	1	1	0	……	0
	:	:	………	:	:	:	:	……	:
	Pavement n	Pavement Improv n	………	0	0	1	1	……	0
Bridge	Bridge 1	Bridge Improv 1	………	1	1	0	1	……	0
	Bridge 2	Bridge Improv 2	………	1	1	0	0	……	1
	:	:	………	:	:	:	:	……	:
	Bridge n	Bridge Improv n	………	0	0	1	0	……	1
Sign	Sign 1	Sign Improv 1	………	1	0	1	0	……	0
	Sign 2	Sign Improv 2	………	1	1	0	1	……	0
	:	:	………	:	:	:	:	……	:
	Sign n	Sign Improv n	………	1	0	1	1	……	1
:	:	:	………	:	:	:	:	……	:
	:	:	………	:	:	:	:	……	:

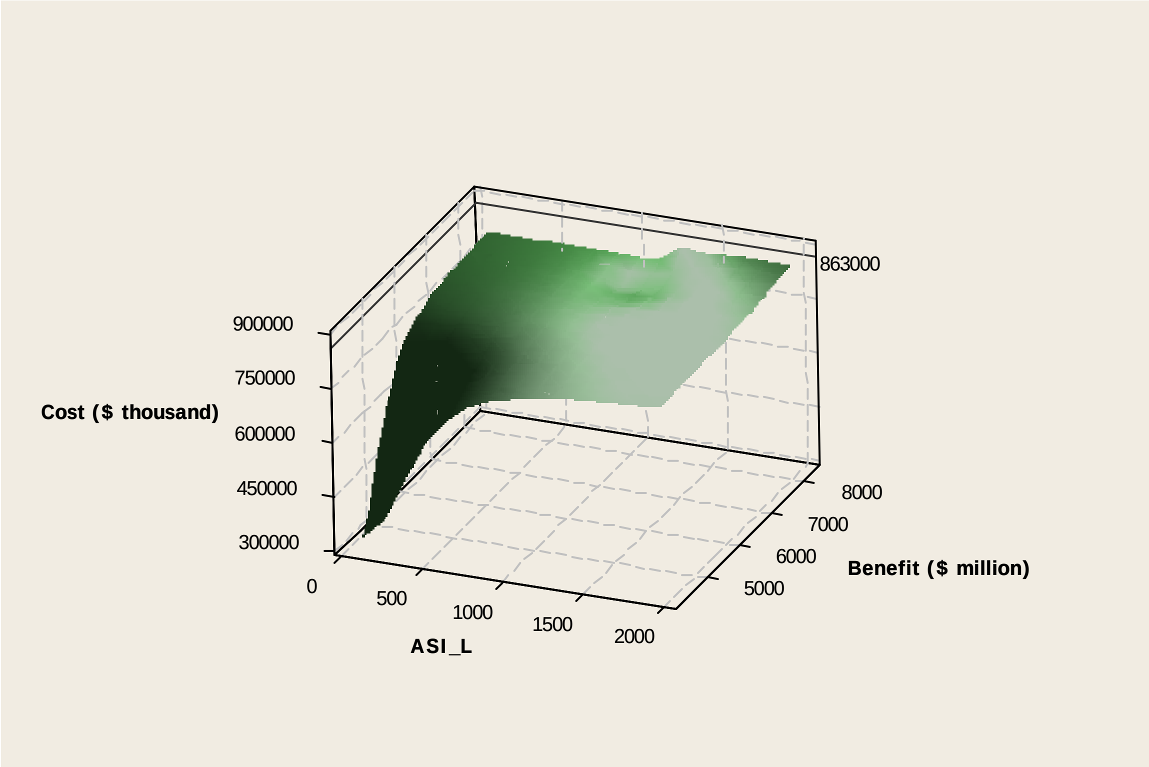
Multiyear integrated parameters

Parameter	
Population size	30
Maximum generations	200
Fitness function(s)	- Overall network ASI -Overall network benefit -Overall network budget -Asset class budgets -Overall condition requirement: 70%, in fair or better condition - Asset classes condition requirement. 70% in fair or better condition
Selection	Ranking Elitist 3%
Crossover rate	85% Multipoint crossover (random single cut point crossover for each asset class sub-string)
Mutations	6%
Immigration rate	6%

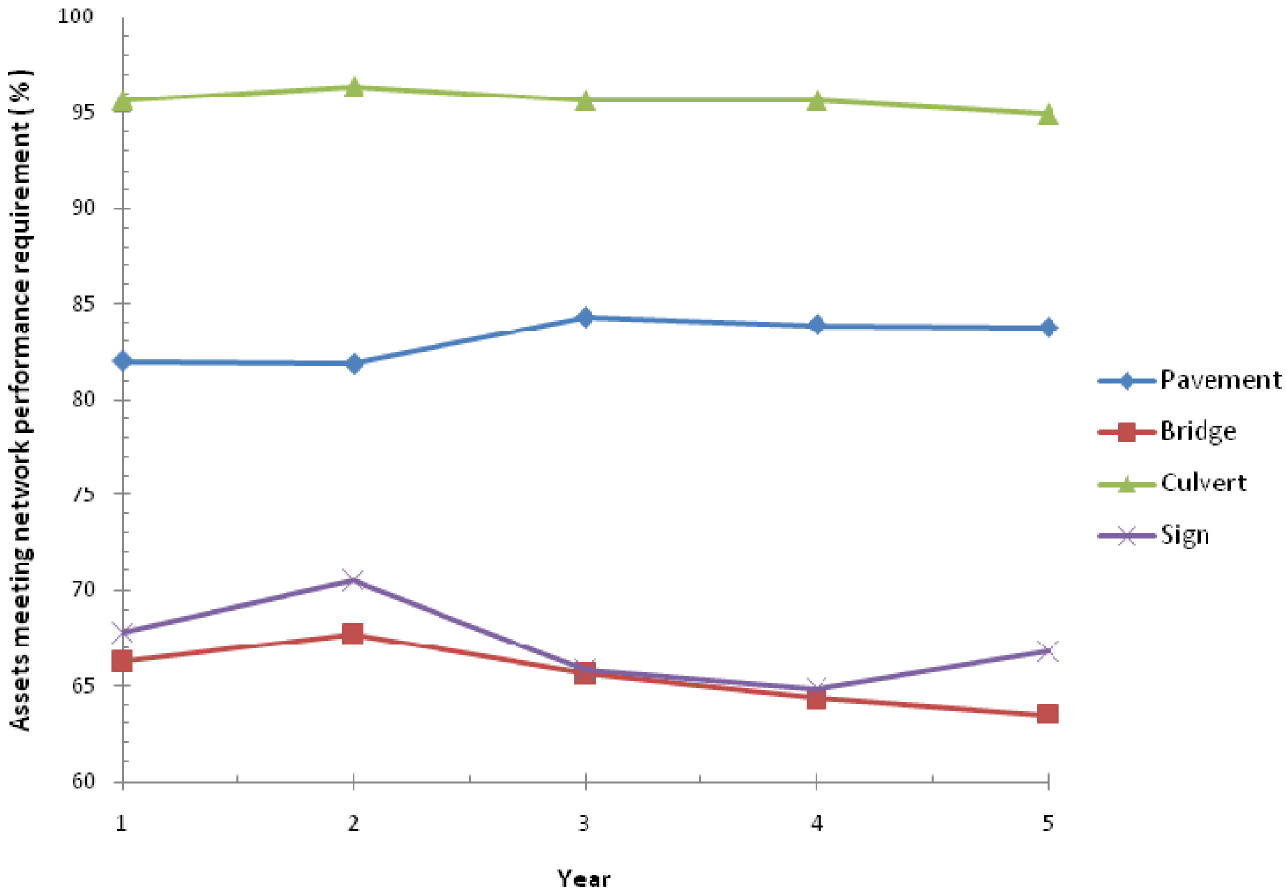
Multiyear integrated process flow



Pareto optimal surface



Network performance over 5-yr horizon



Implementation: Project-Level Integration

- to adjust each years' work program, such that all projects associated with a roadway in planning horizon can be combined into one project and programmed in a single year.

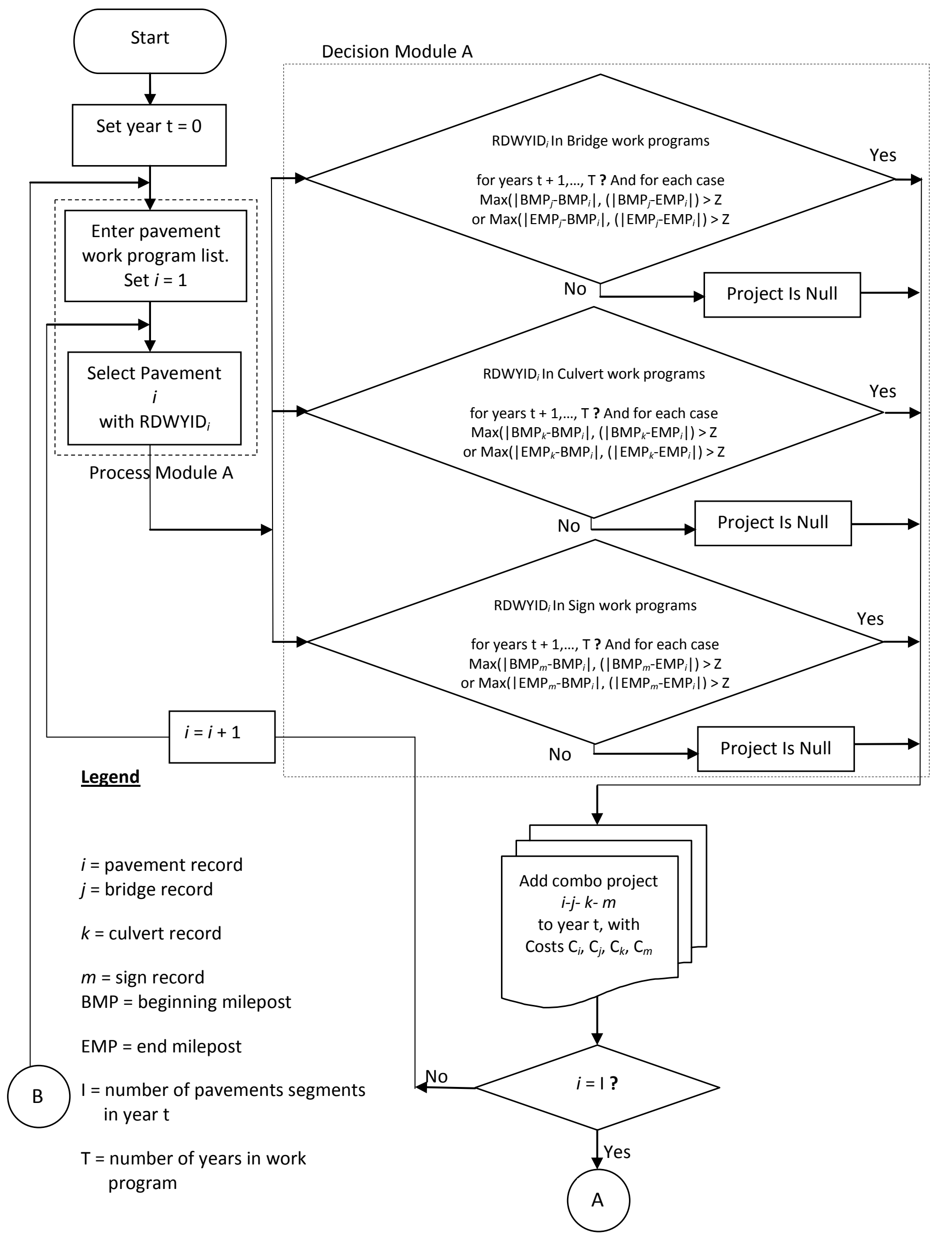
- This approach potentially creates economies of scale leading to reduced costs to an agency.

- Also potential impacts on road users such as delays, detours, and other traffic disruptions will be minimized.

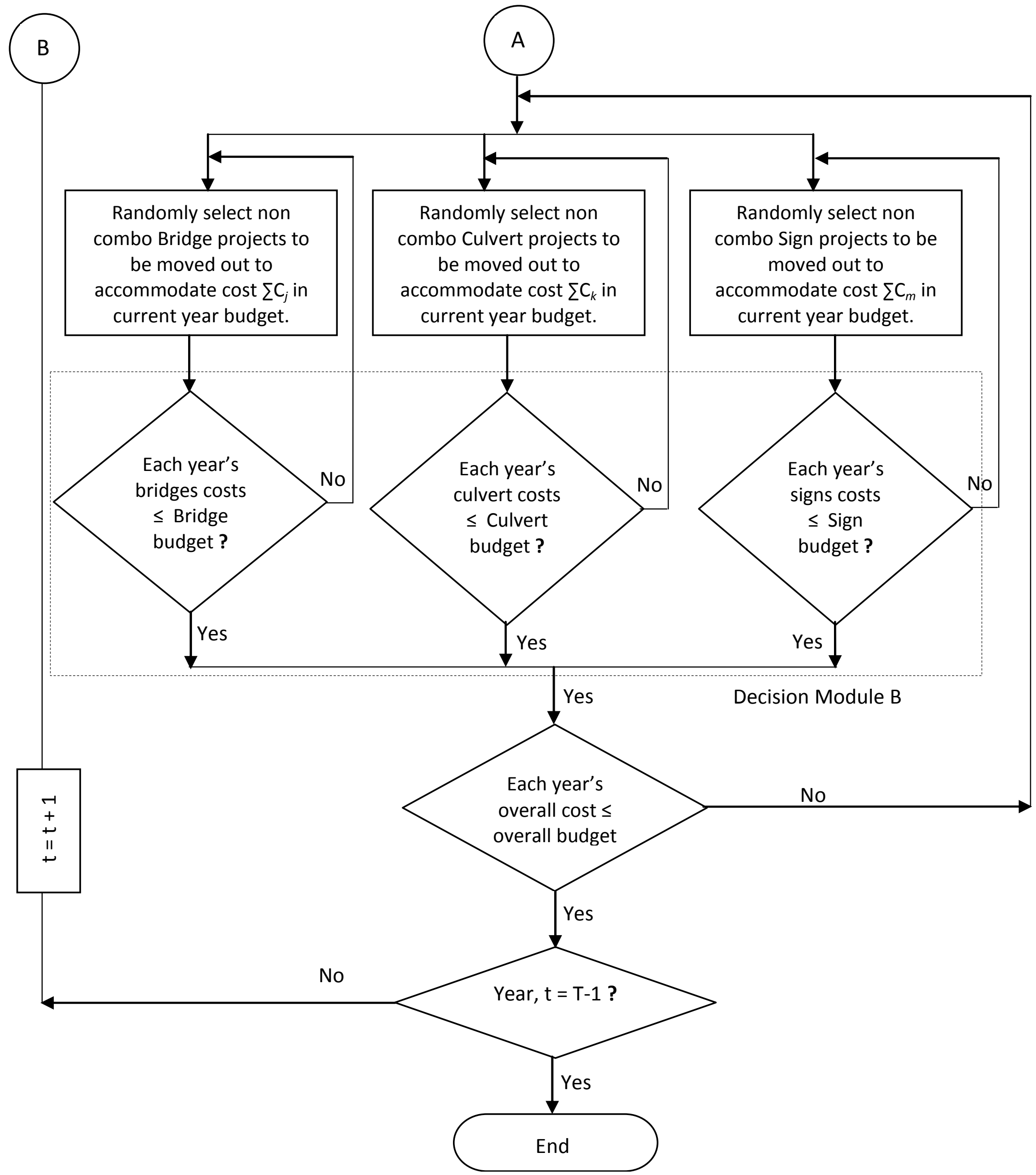
Project-Level Integration

- In this study a database querying approach is adopted, using unique multiattribute identifier of roadway plus begin and end milepoints
- Combined (multi-asset) project will then be programmed for the year of the earliest constituent project, and budget are modified

Project-Level Integration



Project-Level Integration



Project-Level Integration

PAVEMENT PROJECT LIST		
RDWY ID	…	…
79100000	…	…
75270000	…	…
:	:	:

CULVERT PROJECT LIST		
StructureID	RdwyID	…
790048	79100000	…
790049	79100000	…
:	:	:

BRIDGE PROJECT LIST		
StructureID	RdwyID	…
750175	75270000	…
:	:	:

CONTRIBUTIONS

- Reliability-based models using structural reliability index were developed for Florida highway bridges and culverts according to the following classifications:
  - Interstate concrete bridge
  - Non-interstate concrete bridge
  - Interstate prestress bridge
  - Non-interstate prestress bridge
  - Interstate steel bridge
  - Non-interstate steel bridge
  - Interstate culvert
  - Non-interstate culvert

CONTRIBUTIONS

- Deterioration models based on sojourn times in Florida
  - Pavements
    - Interstate Asphalt
    - Non-Interstate Asphalt
    - Interstate Concrete
    - Non-Interstate Concrete
    - Interstate Superpave
    - Non-Interstate Superpave
  - Culvert
    - Interstate culvert
    - Non-Interstate culvert

CONTRIBUTIONS

- A framework for optimizing the “total” infrastructure network in a truly integrated manner was successfully demonstrated
- The GA was demonstrated to be versatile and flexible in accommodating any number of objective functions and constraints
- Project-level integration by database querying techniques was demonstrated

LIMITATIONS

- Data limitations for sojourn times (pavement and culverts) for condition ratings less than 5

- Project-level traffic projections applied exponential growth factors. Investigate the use of a regional transportation model

Future Work

- Develop project-level procedures for other infrastructure assets such storm drains, sewers, guardrail, traffic signal, sidewalks, and bike paths

- Develop sign deterioration models based on retroreflectivity (MUTCD 2009)

- Collect local data to develop deterioration models for specific geographic regions, counties etc.

Future Work

- Develop bridge reliability models based on other reported structural ratings such as inventory rating, sufficiency rating, appraisal rating.

- Develop a whole life process framework (condition and structural reliability) for pavements

- Collaborate results with those of on-going study at Texas A & M Univ for Structural reliability-based models for pavement

CONCLUSIONS

- An integrated approach to transportation infrastructure management was developed and successfully tested

- Multiyear budget allocation within and across asset classes was formulated as a multiyear-multiobjective-capital budgeting problem, and solved by a genetic algorithm

- This study demonstrates how structural reliability can be used as a performance measure over current predominantly condition based measures

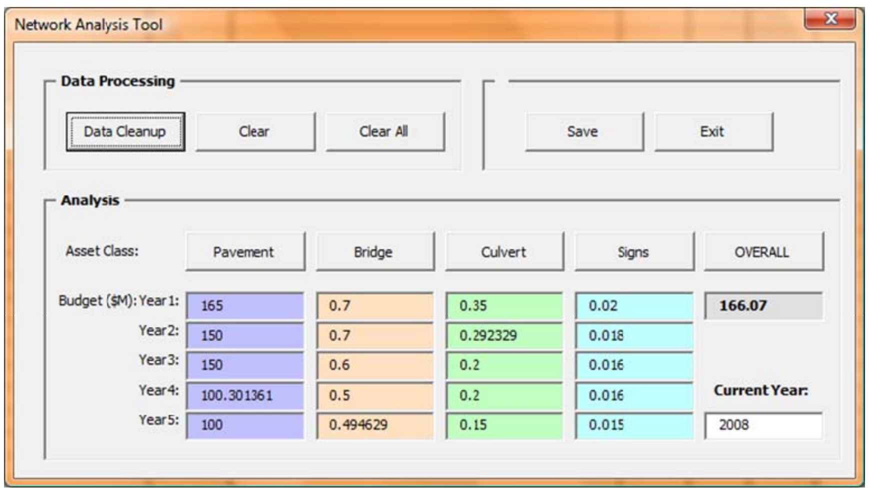
CONCLUSIONS

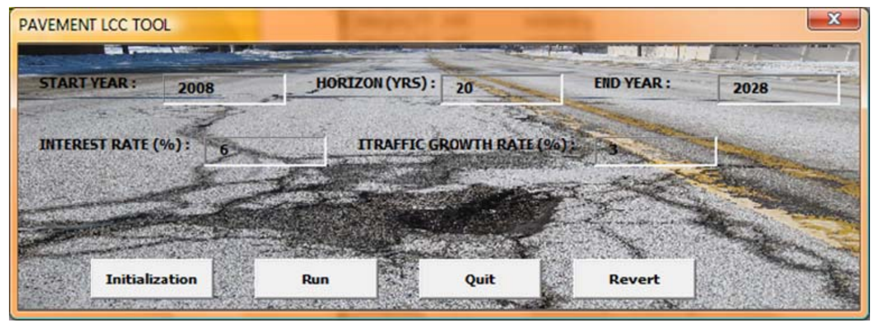
- Whole life process deterioration models were developed for Florida bridges and culverts based on structural reliability

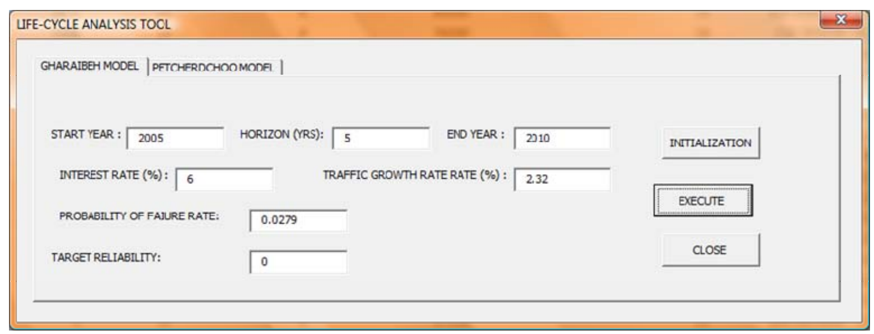
- Sojourn time deterioration models were developed for Florida pavements and culverts based on condition rating

CONCLUSIONS

- Computer-based tools (*Visual Basic*) were developed to implement the procedures developed in this study







ACKNOWLEDGEMENTS

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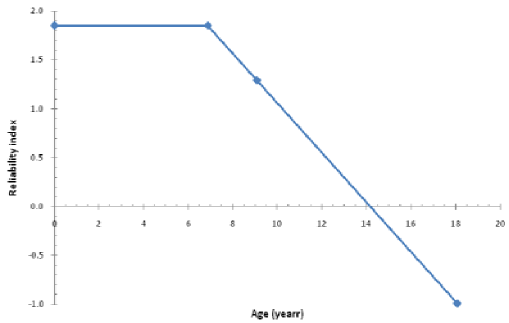
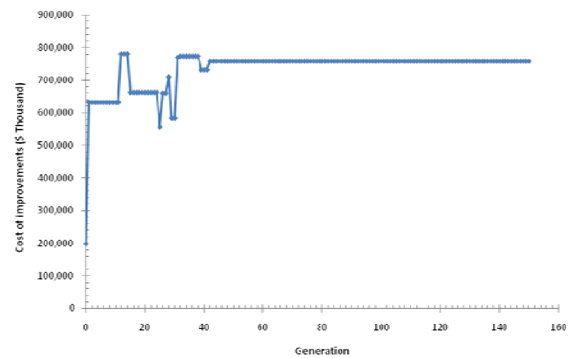
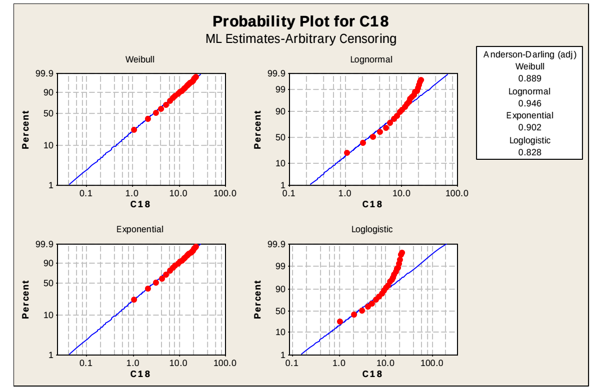
- The committee members, for their time, advice, suggestions, and insights.

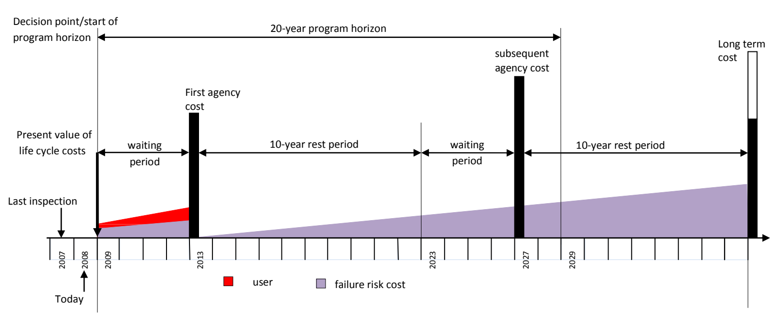
- Family (could not be here today), and friends.

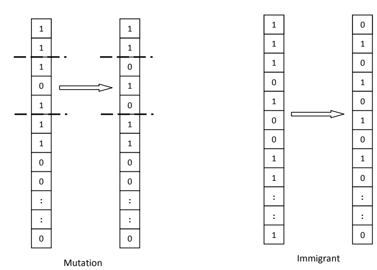


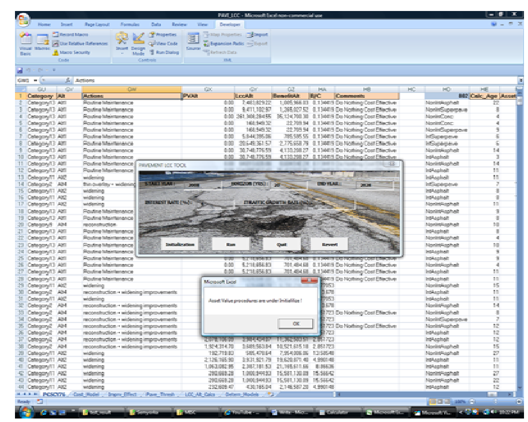




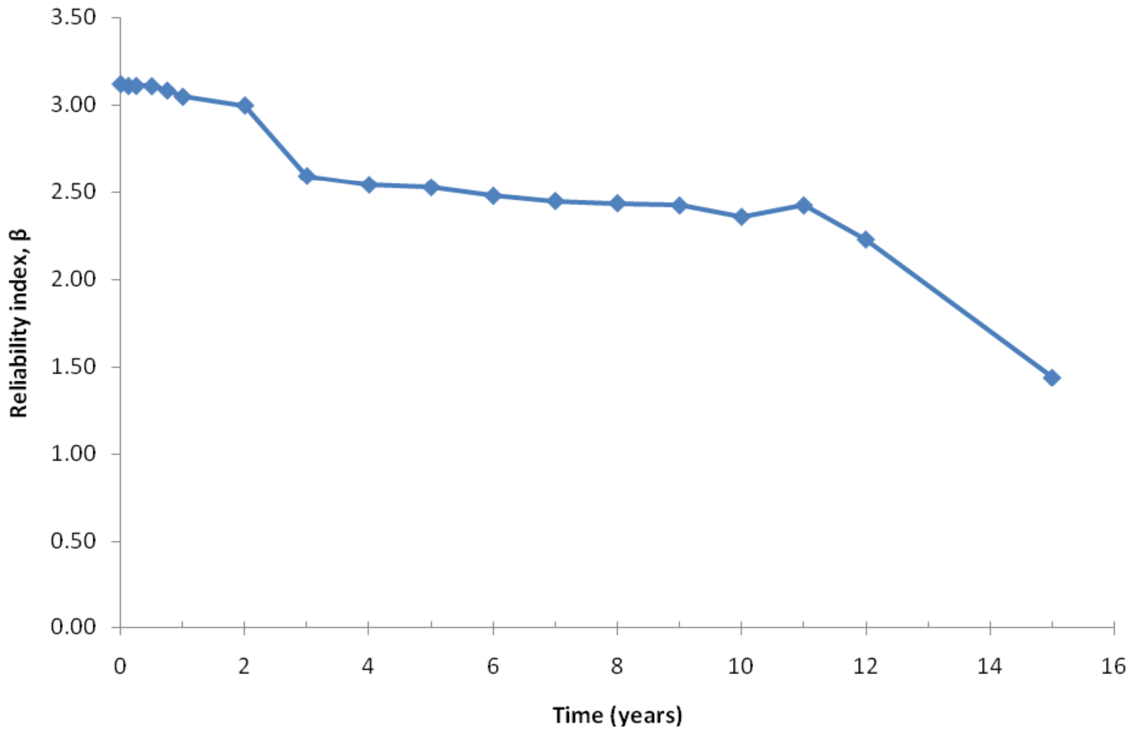
QUESTIONS & COMMENTS ???







Reliability Profile – Interstate Steel Bridge (FL Br 920160)



Budget utilization over 5-yr horizon