Best practices for life cycle design and management of critical infrastructure

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Best Practices for Life Cycle Design and Management of Critical Infrastructure

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Outline

- Background
- Key issues / challenges
- Evolution of infrastructure design and management
- Approaches for infrastructure sustainability and resilience
- Examples
- Epilogue

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Critical Infrastructure

- Roads, bridges, transit, railways, dams, water systems, energy networks
  - Provide core services: transportation, water, energy
  - Critical to economy and quality of life of communities

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Background

- Aging and deterioration of critical infrastructure
- Reductions of levels of service
- Growing concerns for extreme natural & man-made hazards
- Limited available funds for construction and rehabilitation of infrastructures- Infrastructure deficit

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Background

- Infrastructure report cards : ASCE, FCM
- Infrastructure deficits
- Catastrophic failures of some critical infrastructures

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Challenges

- Current design codes/standards
  - Performance-based design for safety and serviceability
  - Prescriptive rules for durability
  - Brittle materials and systems – vulnerable to small, unforeseen perturbations
- Limited modeling of the interactions between infrastructures and natural environments

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Challenges

- Current asset management systems
  - Prescriptive rules for inspection and maintenance
  - Qualitative condition assessment measures
  - Inadequate life cycle performance forecast models
  - Lack of integrated management of different assets: roads, bridges, water - "Silo" Approach
  - Limited consideration for sustainability and resilience

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Challenges

- Considerable uncertainty in infrastructure performance
  - demand, capacity, material properties
  - environment
  - failure consequences
  - life cycle costs
- Need to consider uncertainty associated with infrastructure performance
  - Considerable variability from mean values of key parameters
  - Uncertainty of physical models
  - Uncertainty of events

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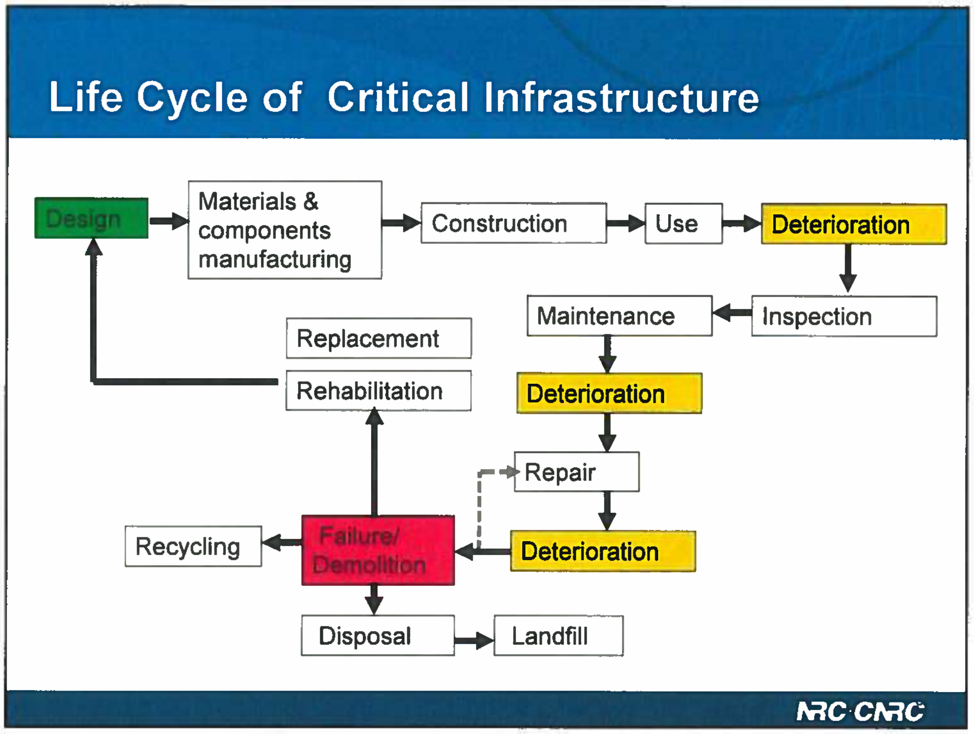
Life Cycle of Critical Infrastructure
Design
Materials & components manufacturing
Construction
Use
Deterioration
Inspection
Maintenance
Deterioration
Repair
Deterioration
Replacement
Rehabilitation
Recycling
Failure/ Demolition
Disposal
Landfill
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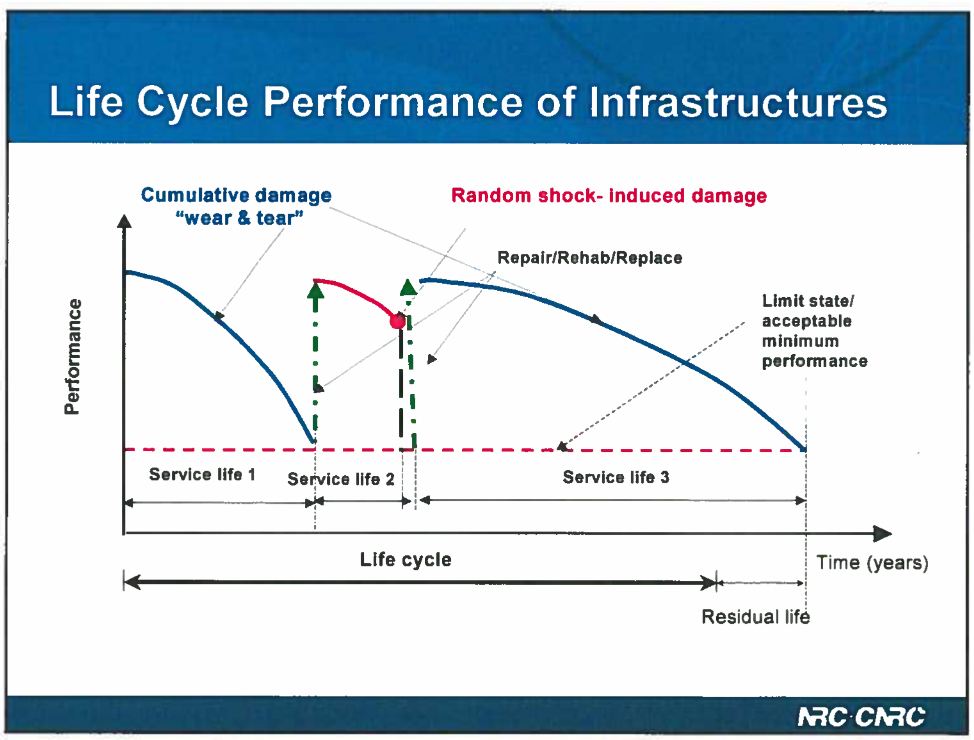
Life Cycle Performance of Infrastructures
Cumulative damage "wear & tear"
Random shock- induced damage
Repair/Rehab/Replace
Limit state/ acceptable minimum performance
Performance
Service life 1
Service life 2
Service life 3
Life cycle
Time (years)
Residual life
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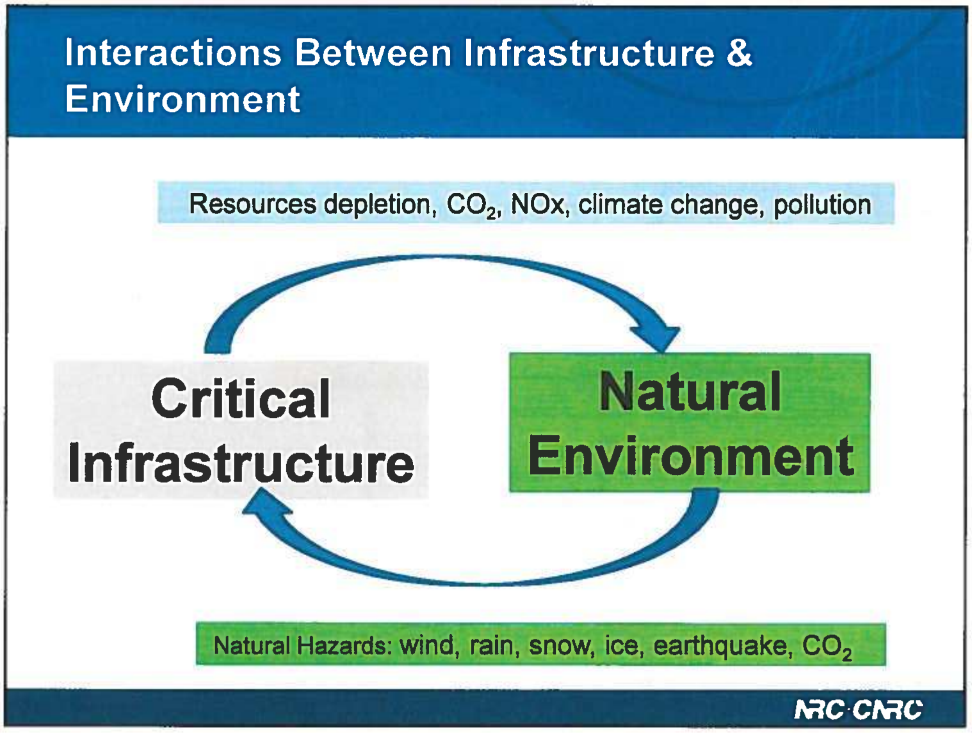
Interactions Between Infrastructure & Environment
Resources depletion, CO_2, NOx, climate change, pollution
Critical Infrastructure
Natural Environment
Natural Hazards: wind, rain, snow, ice, earthquake, CO_2
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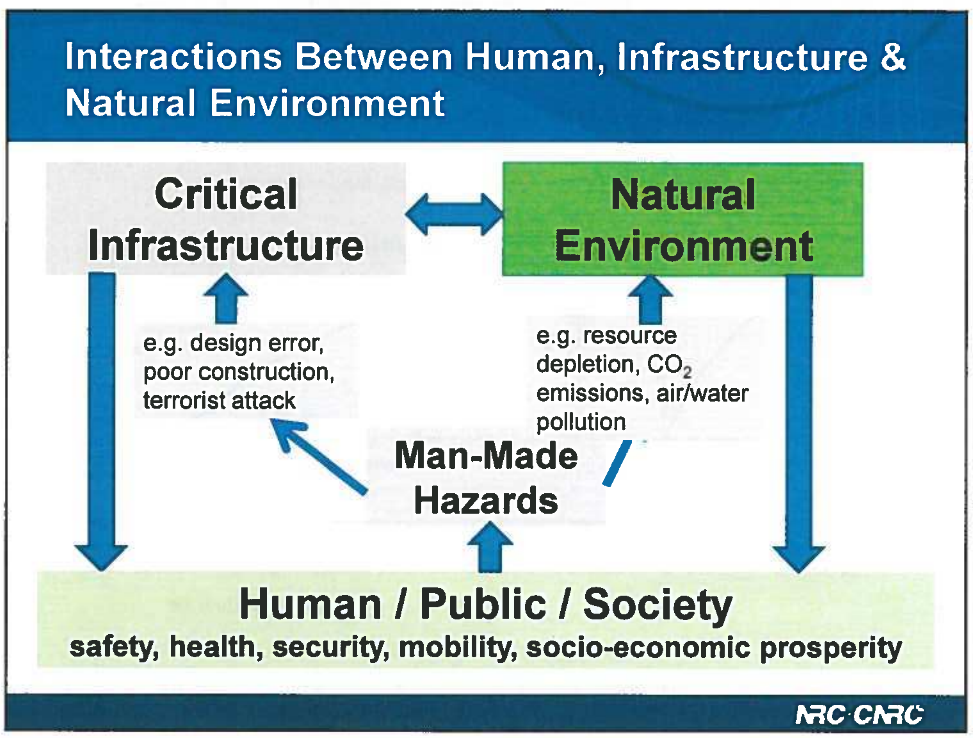
Interactions Between Human, Infrastructure & Natural Environment
Critical Infrastructure
Natural Environment
e.g. design error, poor construction, terrorist attack
e.g. resource depletion, CO_2 emissions, air/water pollution
Man-Made Hazards
Human / Public / Society
safety, health, security, mobility, socio-economic prosperity
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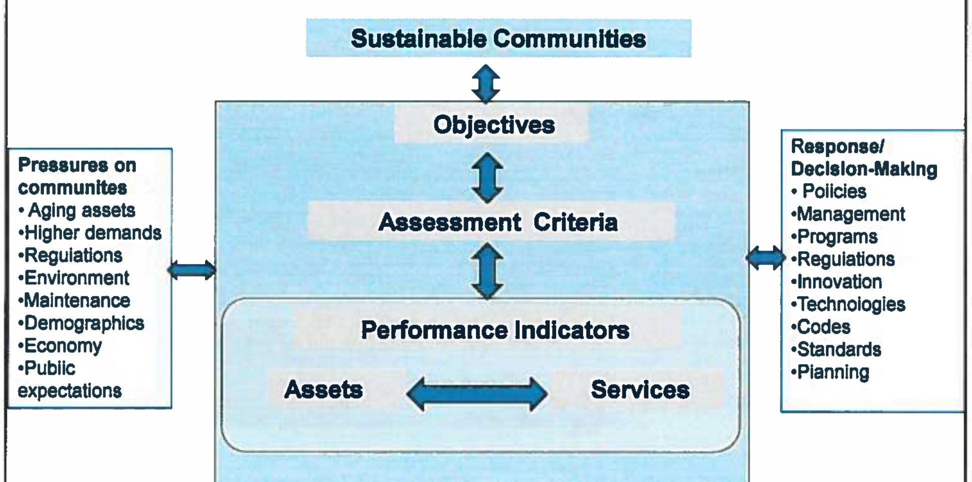
Impacts of Cumulative Damage / Perturbations

Impacts of Extreme Events

Impacts of Extreme Events

Framework for Performance Assessment and Management of Critical Infrastructure



Framework for Performance Assessment and Management of Critical Infrastructure

- Strategic Objectives: Sustainable & Resilient Communities
  - Safety, security, health
  - Mobility
  - Environmental protection
  - Social equity
  - Economic prosperity

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Framework for Performance Assessment and Management of Critical Infrastructure

- Need to integrate management of different assets
- Need to integrate management of assets and services
  - Risk management
  - Maximum return on investment

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Evolution of Design and Management of Critical Infrastructure

Past	Present	Future
- Performance-based design for Safety & Serviceability	- Performance-based design for Safety & Serviceability	- Performance-based design for Safety, Serviceability & Durability
- Prescriptive design for durability	- Prescriptive design for durability	
	- Design for security of critical infrastructures	- Design of Resilient Infrastructures
- Qualitative Condition Assessment	- Qualitative Condition Assessment	- Quantitative Condition Assessment
-Qualitative Asset Management	-Qualitative Asset Management	-Risk-Based Asset Management
	- Green Infrastructure	- Design of Sustainable **Infrastructure:** Environment-Society-Economy - **Smart Infrastructure**

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Solutions: Innovative Technologies

- High performance materials
  - High /ultra high performance concrete
  - Corrosion-resistant steel
  - Super strength reinforcement
  - Fiber-reinforced polymers
- Smart infrastructures
  - Smart damage detection
  - Continuous intelligent health and security monitoring
  - Data-driven asset management

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Solutions: Infrastructure Regulations

- Standards & Codes for Performance-Based Durability Design
- Life Cycle Design and Management Approaches for Sustainable Infrastructures: Economic-Social & Environmental Sustainability
- Design of Resilient Infrastructures Against Low Likelihood & High Consequences Events: Infrastructure safety and security

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Sustainability & Resilience: Concepts & Definitions

Sustainability is the capacity to:

- Meet the needs of present and future generations
- Curb our consumption of resources and emissions
- Protect environment
- Social equity
- Economic prosperity

Resilience is the capacity to:

- Resist unexpected events (bomb blast)
- Adapt to change (e.g., high wind loads)
- Survive catastrophes

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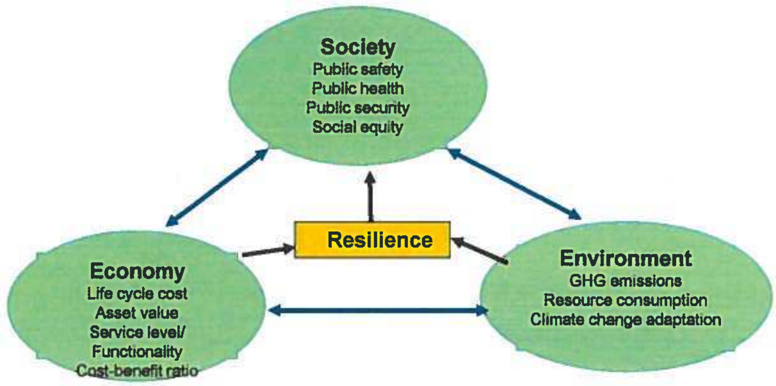
Resilient and Sustainable Infrastructure



(Model Framework NRTSI/NRC 2009)
http://www.nrtsi.ca/documents/Framework.E.pdf

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Modes of Infrastructure Failure

- **Loss of structural integrity of asset**
Failure is the inability of a structural system or one of its primary load-carrying components to perform its intended function.

- **Loss of functionality/ reduction of level of service**
Failure is the inability of an infrastructure system to provide the level of functionality or service it was designed for.

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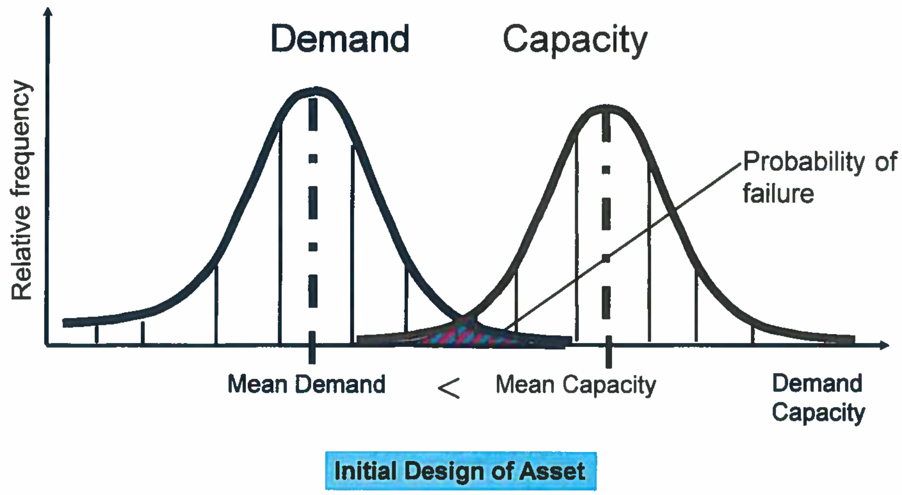
Risk of Failure of Infrastructure Systems



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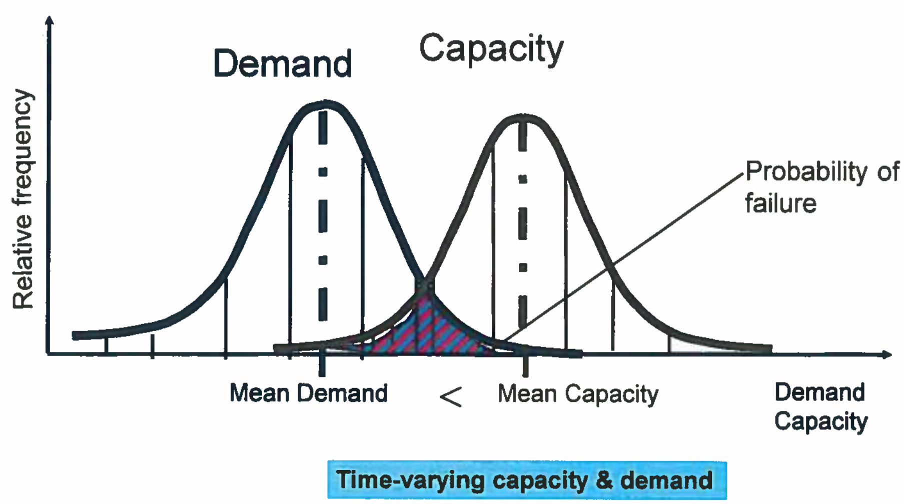
Risk of Failure of Infrastructure Systems



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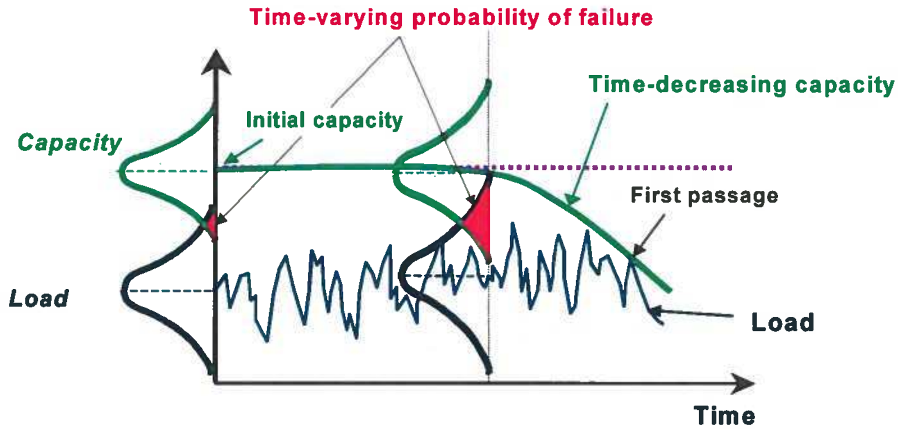
Time-Varying Probability of Failure



Risk of Failure of Infrastructure Systems

- Risk of failure=Probability of failure X Consequences of failure

- Probability of failure

P [Capacity< Demand] < Pacceptable

- Consequences of failure
  - Social
  - Economic
  - Environmental

Consequences of Failure

- Social impacts
  - fatalities, injuries
  - illnesses
- Economic impacts
  - maintenance, rehab/replacement costs
  - liability costs
  - loss of functionality /disruption of services
  - recovery time
- Environmental impacts
  - CO_2 emissions
  - Contamination of air, water, soil
  - waste materials

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Towards Sustainable & Resilient Critical Infrastructures

- Physical integrity of assets
  - Acceptable levels of structural safety
  - Acceptable levels of serviceability
  - Resilient/robust systems
- Acceptable levels of service/ functionality
- Long service life
- Minimum life cycle costs
- Acceptable risks of failure

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Examples of Resilient and Sustainable Infrastructure Solutions

- Risk-based long term planning of design and maintenance of sustainable infrastructure
- Green infrastructure
- Resilient infrastructure against bomb blast
- Smart critical infrastructure

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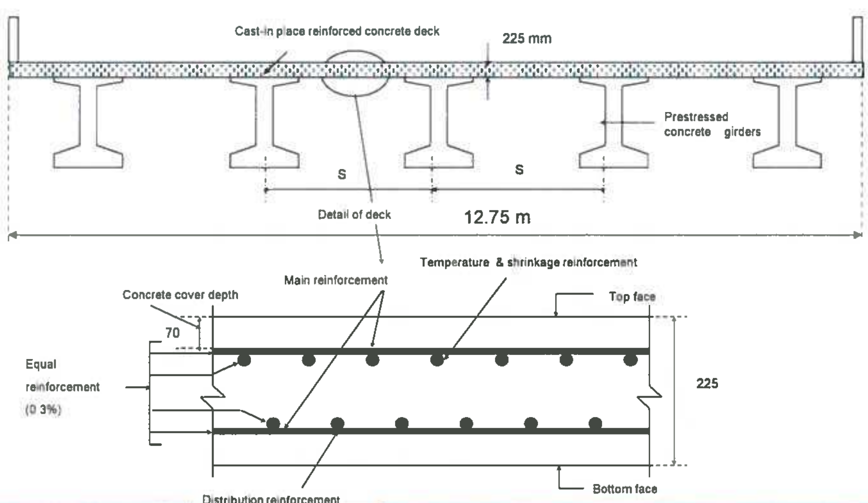
Example: Sustainable Highway Bridge

Bridge length = 47.5 m



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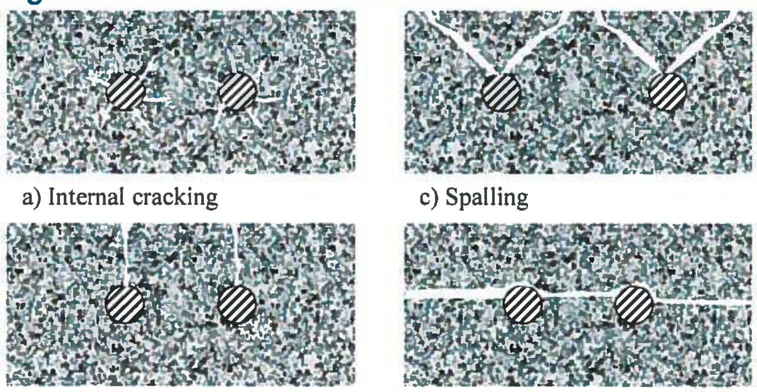
Failure Modes

- Corrosion of reinforcing steel
- Internal cracking
- Spalling and delamination of deck



a) Internal cracking
c) Spalling
b) Surface cracking
d) Delamination

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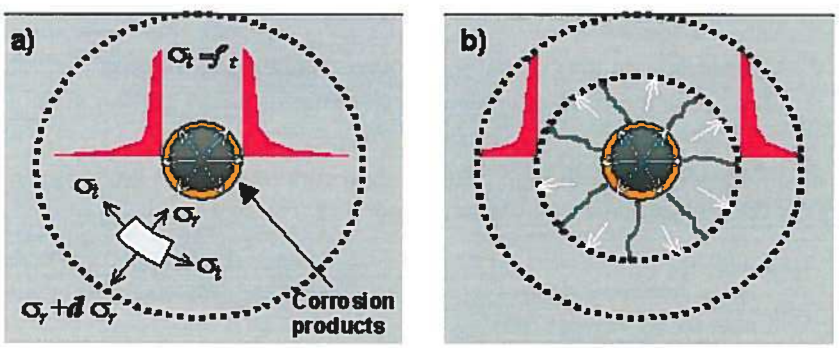
Failure Mode: Concrete Deck Spalling



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Life Cycle Design and Maintenance Planning

- Use of high performance concrete
- Use of corrosion-resistant steel (stainless , galvanized)
- Use of glass-fiber reinforced polymer (GFRP) reinforcing bars
- Increase concrete cover depth
- Patch repairs of damaged deck
- Rehabilitation of chloride-contaminated concrete cover
- Replacement of deck

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Long Term Maintenance Planning

•Focus on 2 life extension strategies:

i. Rehabilitation and replacement with conventional normal performance concrete (NPC) deck reinforced with carbon steel

ii. Replacement with high performance concrete (HPC) technology deck reinforced with carbon steel

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Long Term Maintenance Planning

- Criteria:
  - Social Sustainability: Minimize fatalities, injuries, traffic delays
  - Economic Sustainability: Minimize life cycle costs, users' costs
  - Environmental Sustainability: Minimize CO2 emissions and construction material waste

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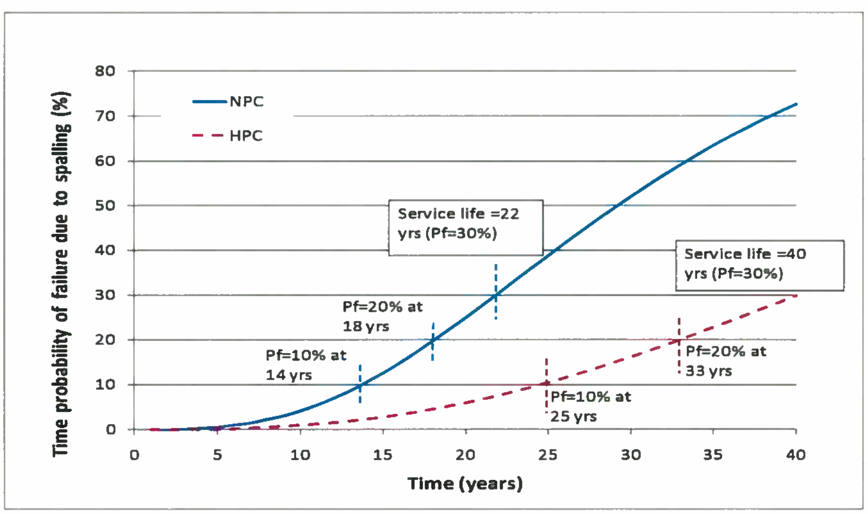
Time-Varying Probability of Failure



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Expected Service Life

- Failure/End of life: Probability of spalling= 30%
- Expected service life
  - 22 years for conventional concrete bridge deck (NPC)
  - 40 years for high performance concrete bridge deck (HPC)

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Travel Delay Costs

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Travel Delay Costs

Maximum speed: 100km/h

Actual average speed: 20km/h

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Travel Delay Costs

- Length of highway affected by activity
- Traffic speed during activity
- Normal traffic speed
- Durations of maintenance, rehabilitation, and replacement activities
- Annual average daily traffic (AADT)
- Annual average daily truck traffic (AADTT)
- Average values of automobile and truck drivers time
  - $12/hr for automobile drivers
  - $20/hr for truck drivers

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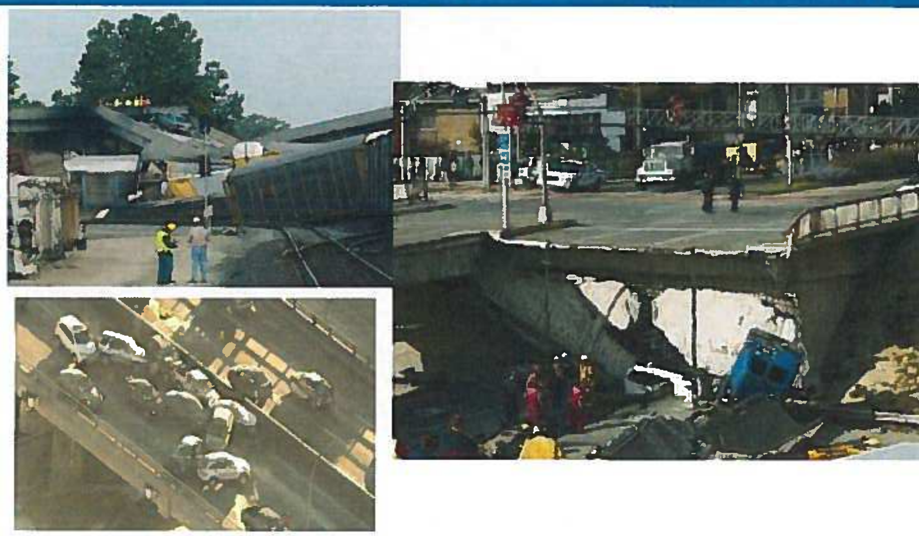
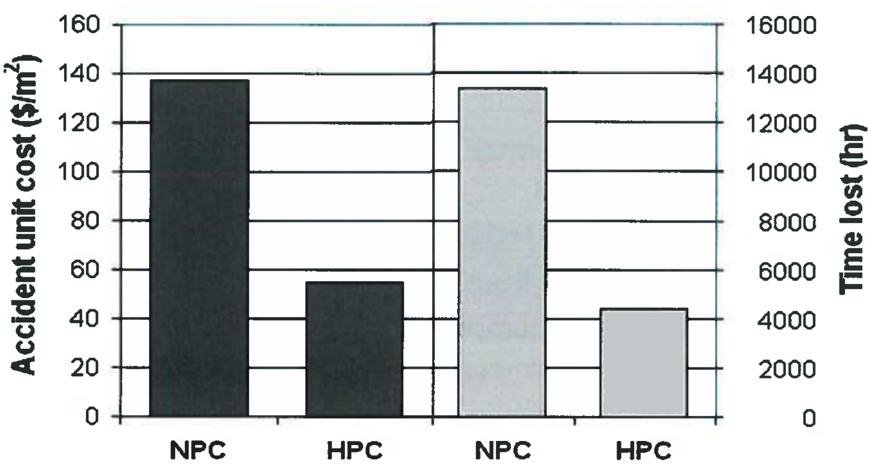
Traffic Accidents due to Failure



Travel Delay and Accident Costs



Total Costs

- Life cycle= 40 years
- Discount rate= 3%
- Present value life cycle costs:
  - Initial construction costs
  - Discounted cost of inspections
  - Discounted costs of repairs and rehabilitation
  - Discounted costs of replacement
  - Discounted salvage value
  - Discounted travel delay and accident costs

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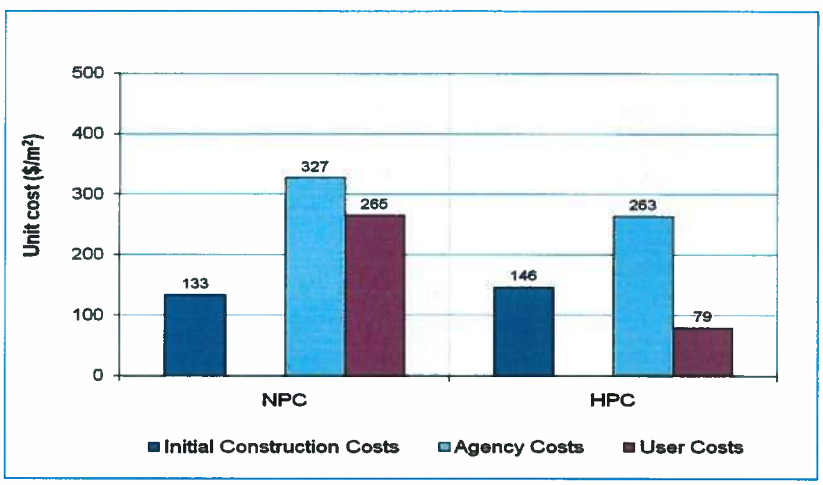
Total Life Cycle Costs



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Green Bridge Infrastructure

- Green concrete technology:
  - Replace 25% of cement by fly ash
  - Fly ash: by-product of coal production with cementing properties
  - Replacement of 1Ton of cement reduces 1Ton of CO2 emissions

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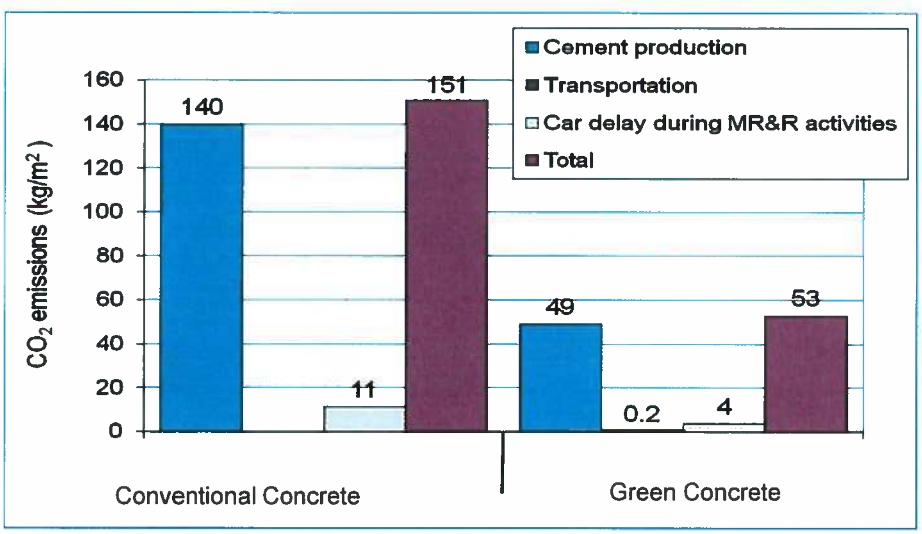
Life Cycle CO_2 Emissions



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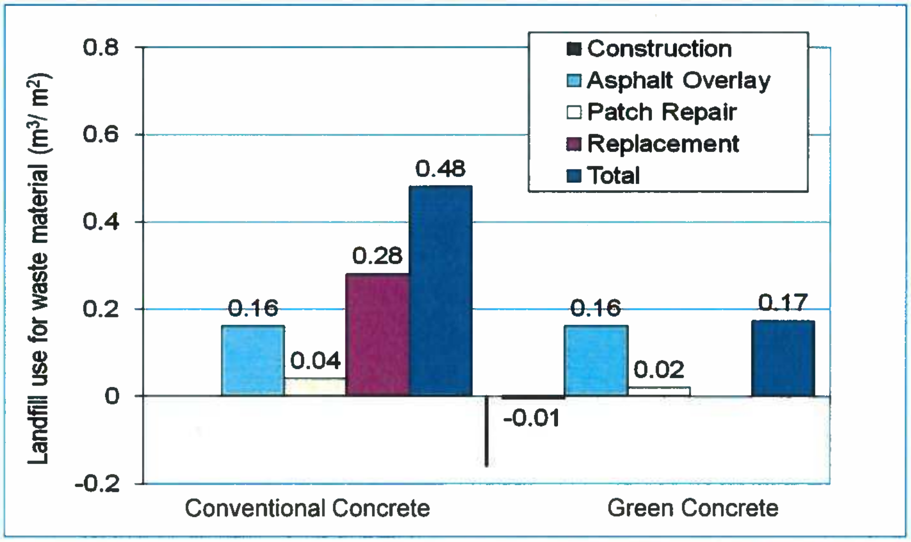
Life Cycle Waste Materials Production



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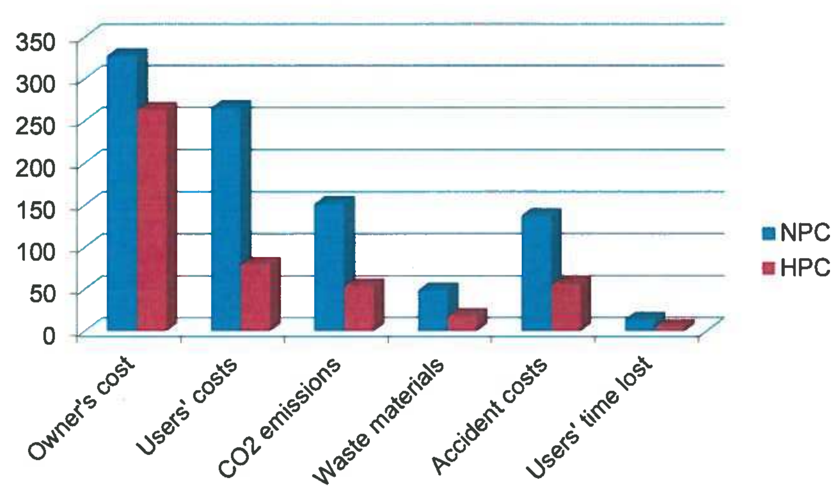
Design of Sustainable Highway Bridge Decks



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Example: Smart Critical Infrastructure

- Smart sensors for damage detection and health monitoring
- Continuous data acquisition of:
  - Materials properties
  - Demand and capacity of assets
  - Levels of service
- "Big Data" storage & processing
- Data analysis and decision support
- Continuous risk assessment and management
- Communication to stakeholders

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Conclusions

- Sustainability and resilience criteria need to be considered at the design stage and at the long term management stage of critical infrastructures

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Conclusions

- Risk-based design and management approaches to enhance the sustainability and resilience of infrastructures that consider:
  - All potential hazards
  - All direct and indirect consequences
  - Relevant measures of sustainability and resilience
  - Uncertainty and time/space dependence in events, parameters and physical models captured by probabilistic models

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Epilogue

To achieve sustainable and resilient critical infrastructure there is a need to develop innovative materials, regulations and comprehensive risk-based design and management approaches that enable infrastructure systems to provide:

- Long life and low maintenance assets
- High resistance and functionality under small perturbations
- Remote and continuous monitoring of high risk infrastructures
- Consideration of socio-economic, and environmental impacts of critical infrastructures

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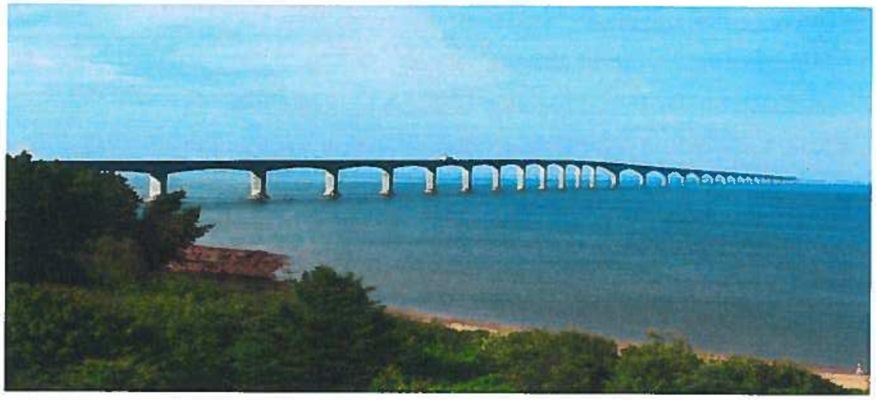
Longest (12.9 km) *bridge* over ice covered waters in the world, joining *Borden-Carleton, Prince Edward Island & Cape Jourimain*, New-Brunswick. Completed in 1997. Total construction cost= $1B. Service Life =100 years.



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Thank you

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