IOWA STATE UNIVERSITY

11th International Conference on Transportation Asset Management

Investigation of Climate Change Effects on Transportation Asset Management

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Causes of Climate Change

Climate change is believed to be originated from:

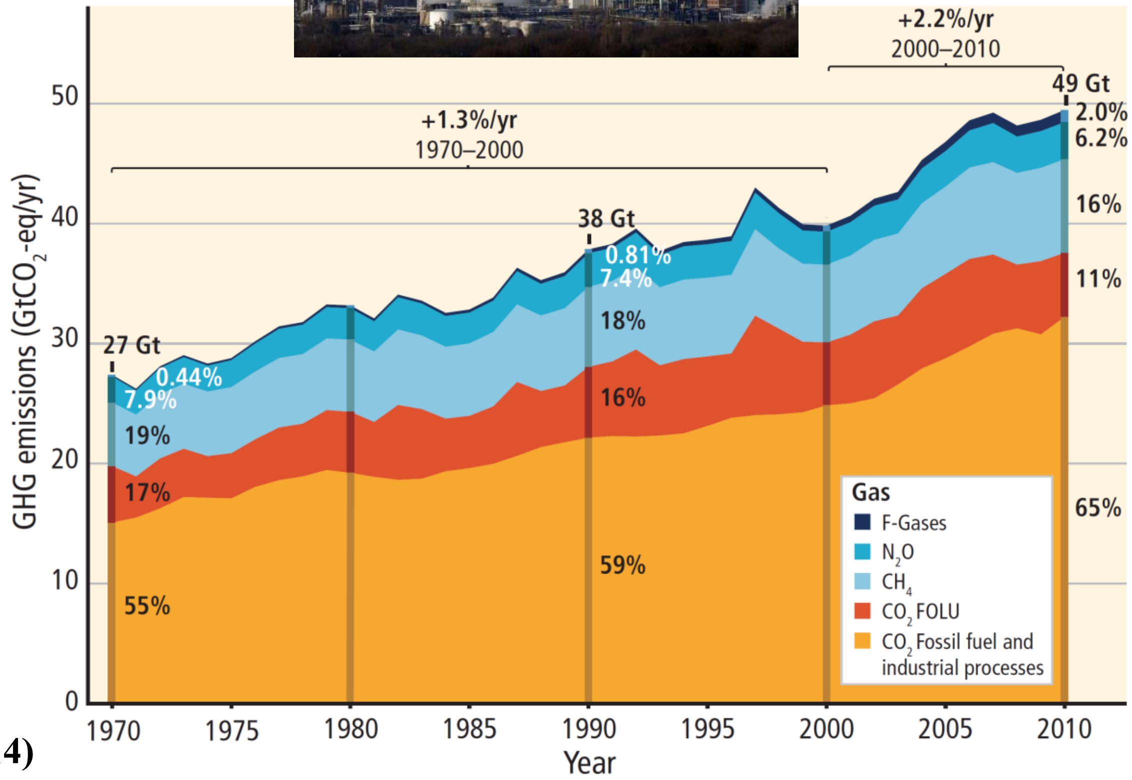
- Natural sources
- Anthropogenic sources

    Fossil fuel

    Agriculture

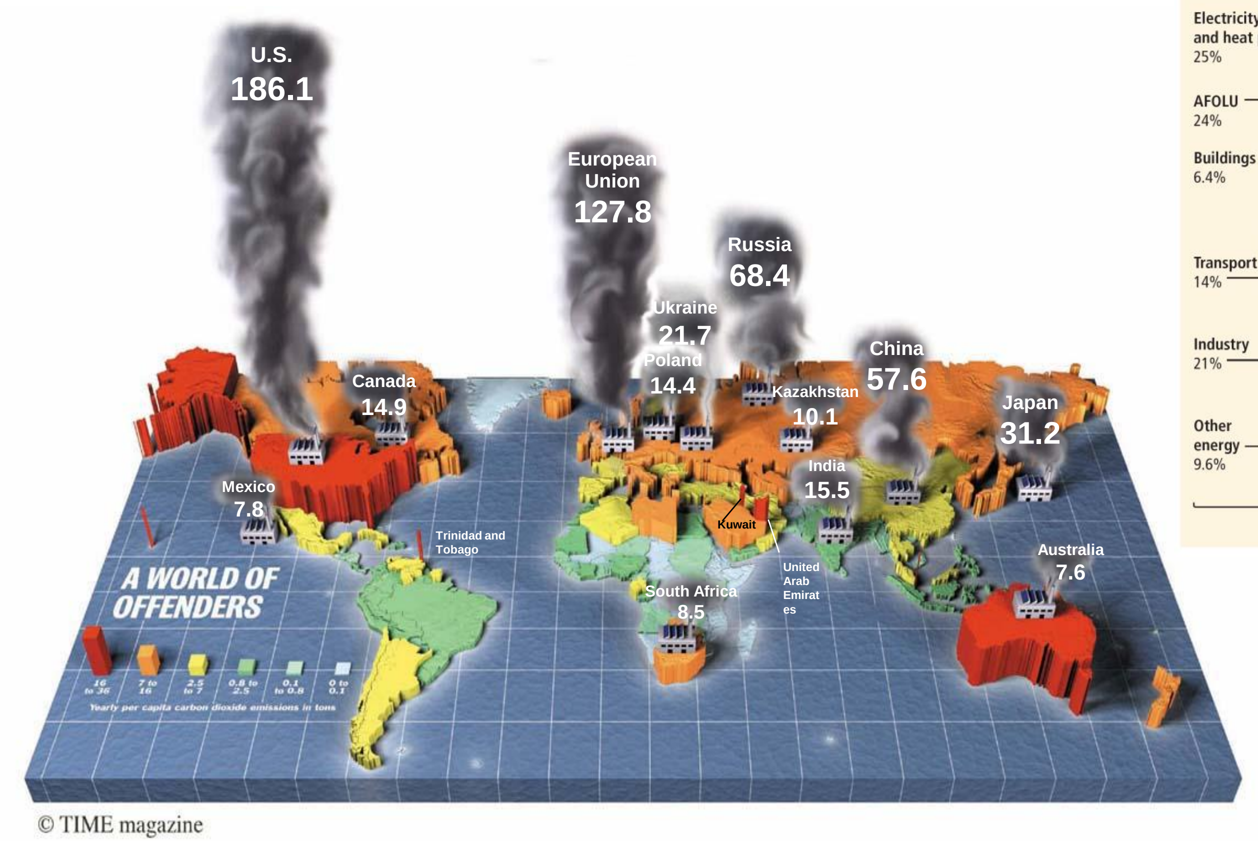
Greenhouse gases (GHG)

- CO_2: 76%
- CH_4: 16%
- N_2O: 6%
- F-Gases: 2%

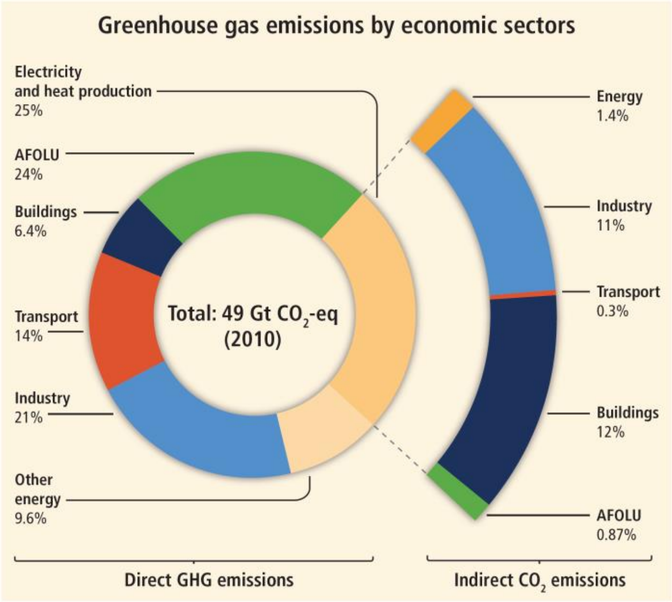


IPCC5 (2014)

Contributors to GHG Emission



CO_2 emissions in billions of tons (1950-2001)

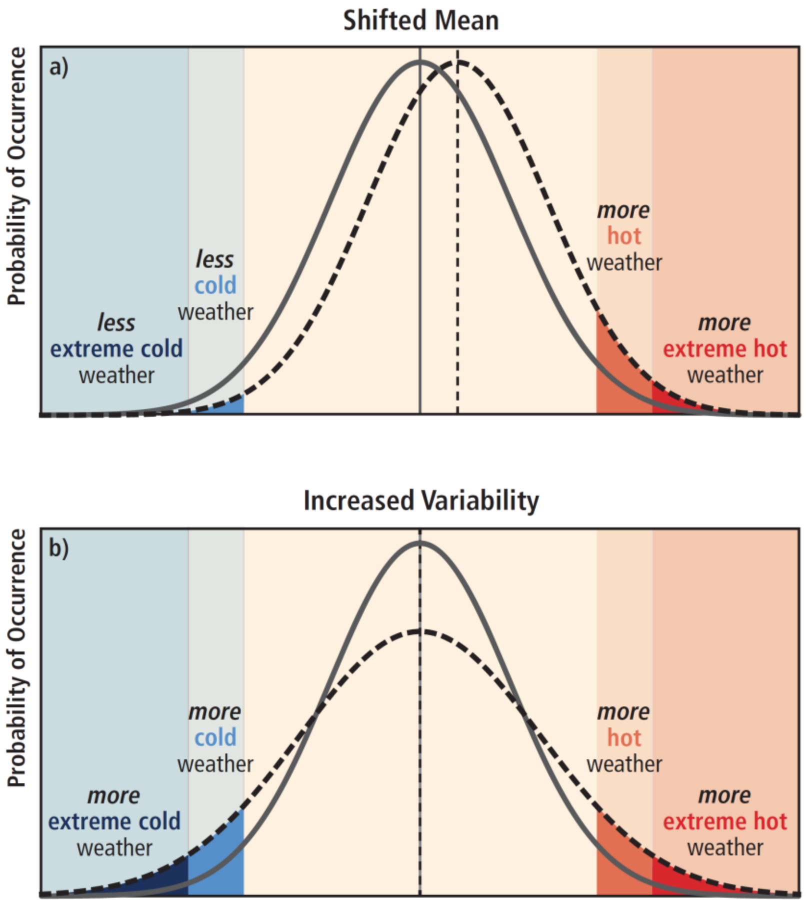


IPCC5 (2014)

Consequences of Climate Change

Possible threats:

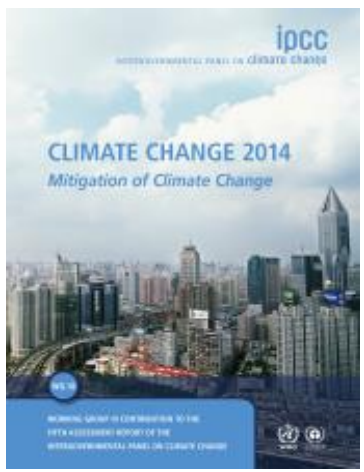
- Change of ecosystem
- Spread of diseases
- Flooding and sea level rise
- Increase of extreme weather events



IPCC4 (2012)

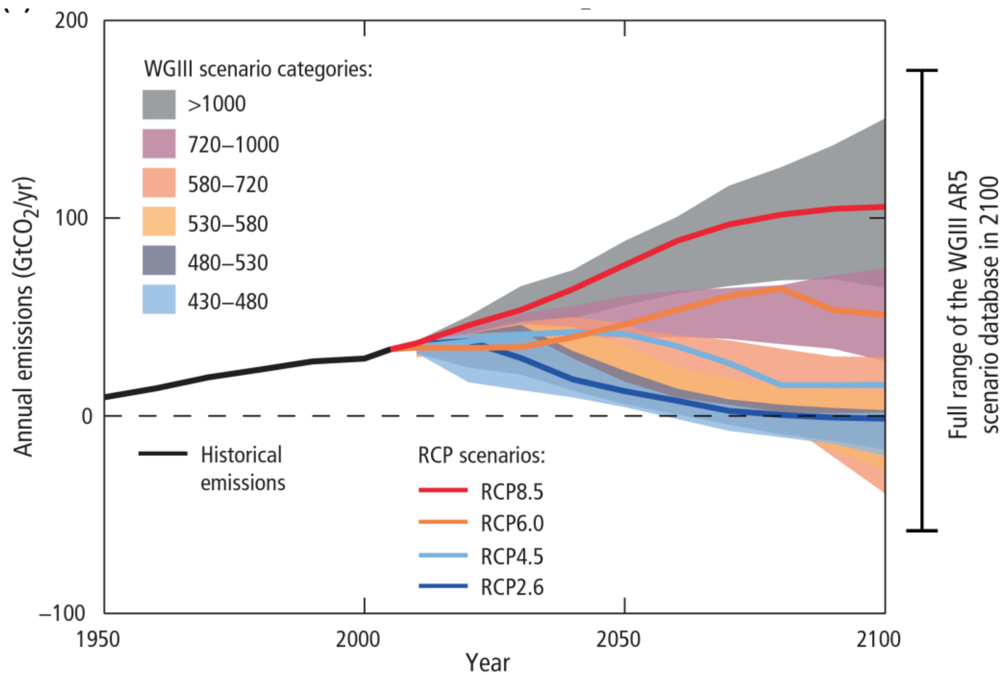
Investigation of Climate Change Effects

Intergovernmental Panel on Climate Change (IPCC) is the leading international body for climate change. It is established by the United Nations Environment Program (UNEP) and World Meteorological Organization (WMO) in 1988. Currently, 195 countries are members of the IPCC.



IPCC Climate Change Scenarios

- Atmospheric changes (temperature/humidity)
- Extreme events / Future risks
- Sea level and ocean condition
- Adaptation and mitigation



Fourth Assessment (2007)

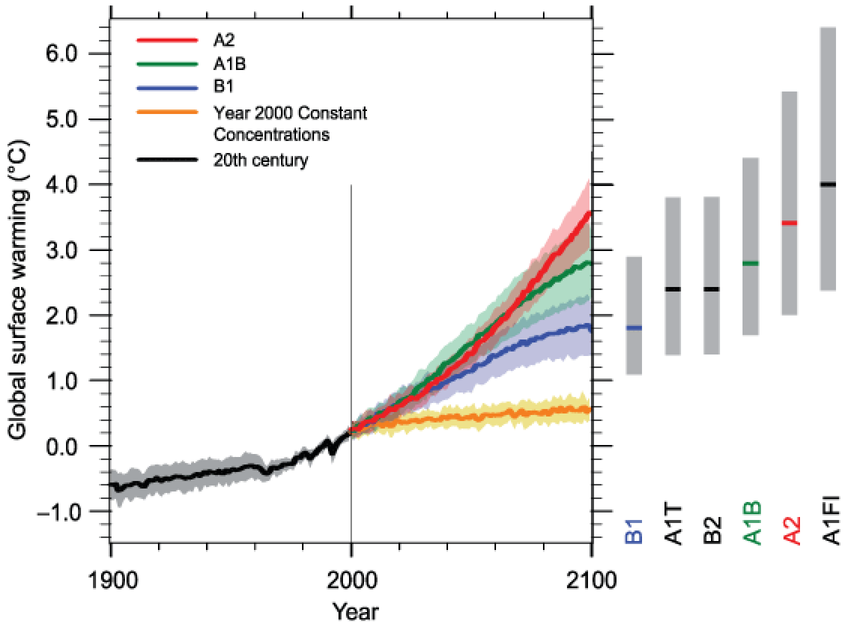
Scenarios:
A1{A1F, A1T, A1B}
A2, B1, B2

Fifth Assessment (2014)

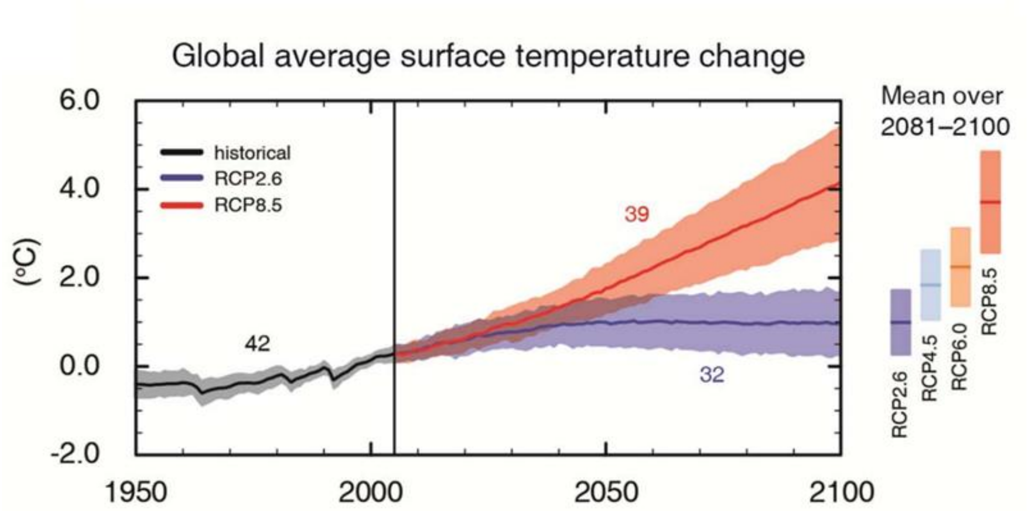
Scenarios:
RCP8.5, RCP6.0
RCP4.5, RCP2.6

Average Surface Temperature Change

Fourth Assessment (2007)



Fifth Assessment (2014)



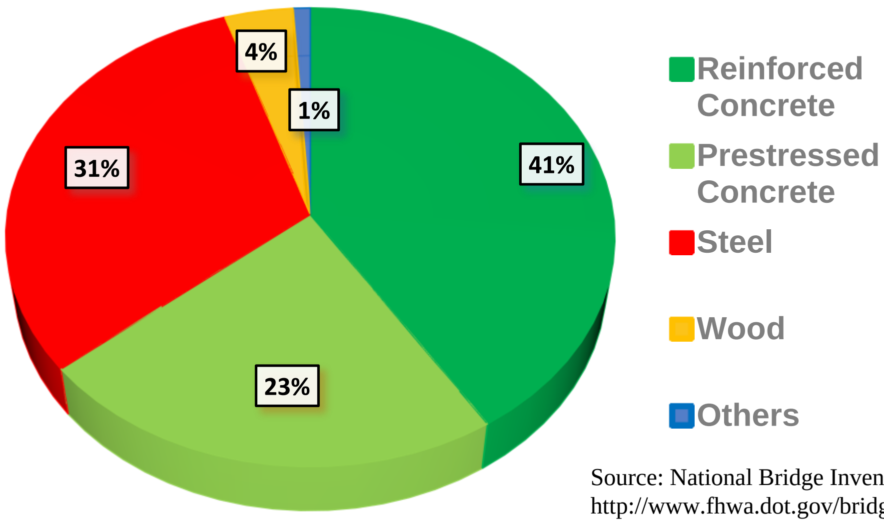
Important Factors:

- Global population
- Economic condition
- Technological changes

Deteriorating Infrastructure Components

- There are approximately 173,000 structurally deficient bridges in the U.S.
- Corrosion is one of the major causes of deterioration in RC structures.

Total number of bridges in the U.S.: ~ 600,000



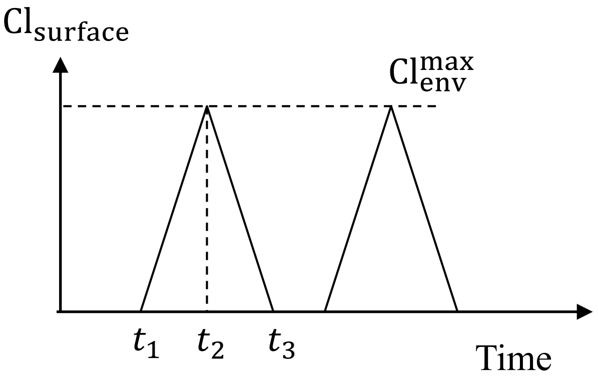
Source: National Bridge Inventory
http://www.fhwa.dot.gov/bridge/britab.cfm

Effects of Environmental Stressors

- Carbon dioxide penetration
- Chloride penetration
  - Exposure to chloride from sea water
  - Exposure to chloride from deicing salt

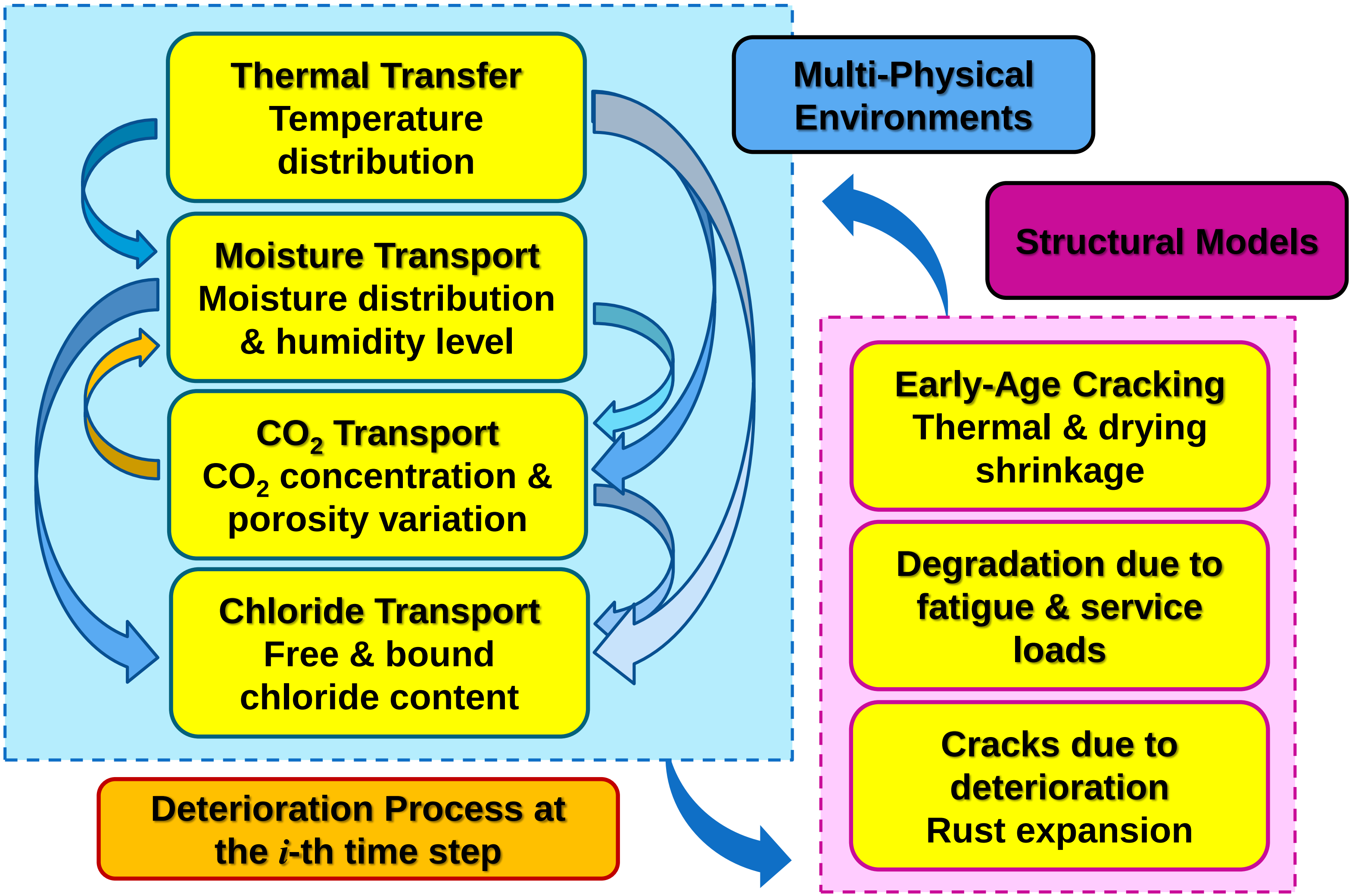
$$\mathrm{Cl}_{surface} = \begin{cases} 2.95 & d < 0.1 \text{ km} \\ 1.15\text{-}1.81 \log(d) & 0.1 \le d < 2.84 \\ 0.35 & d > 2.84 \end{cases}$$

$$\mathrm{Cl}_{surface} = \begin{cases} 0 & t < t_1 \\ \mathrm{Cl}_{env}^{max}(t-t_1)/(t_2-t_1) & t_1 \le t < t_2 \\ \mathrm{Cl}_{env}^{max}[1-(t-t_2)/(t_2-t_1)] & t_2 \le t < t_3 \end{cases}$$



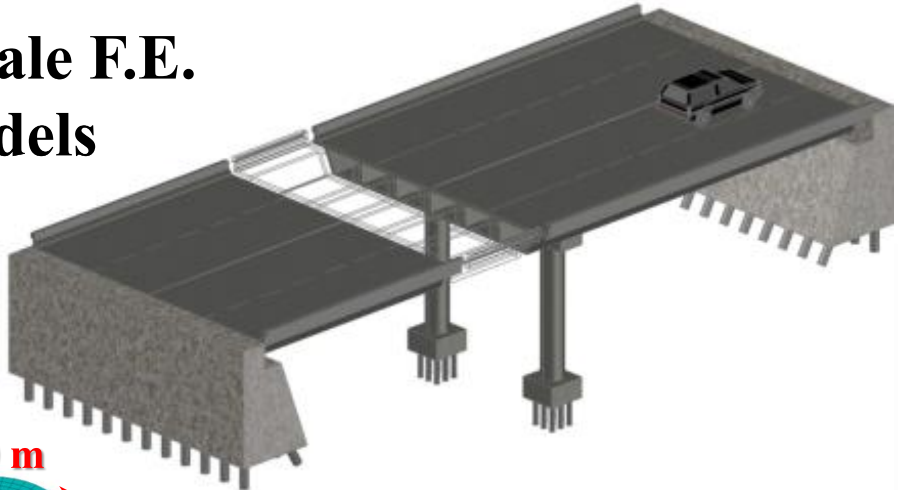
- Temperature changes
- Humidity fluctuations

Computational Framework

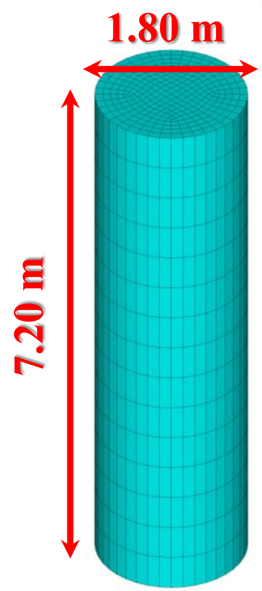


Full-Scale Structural Models

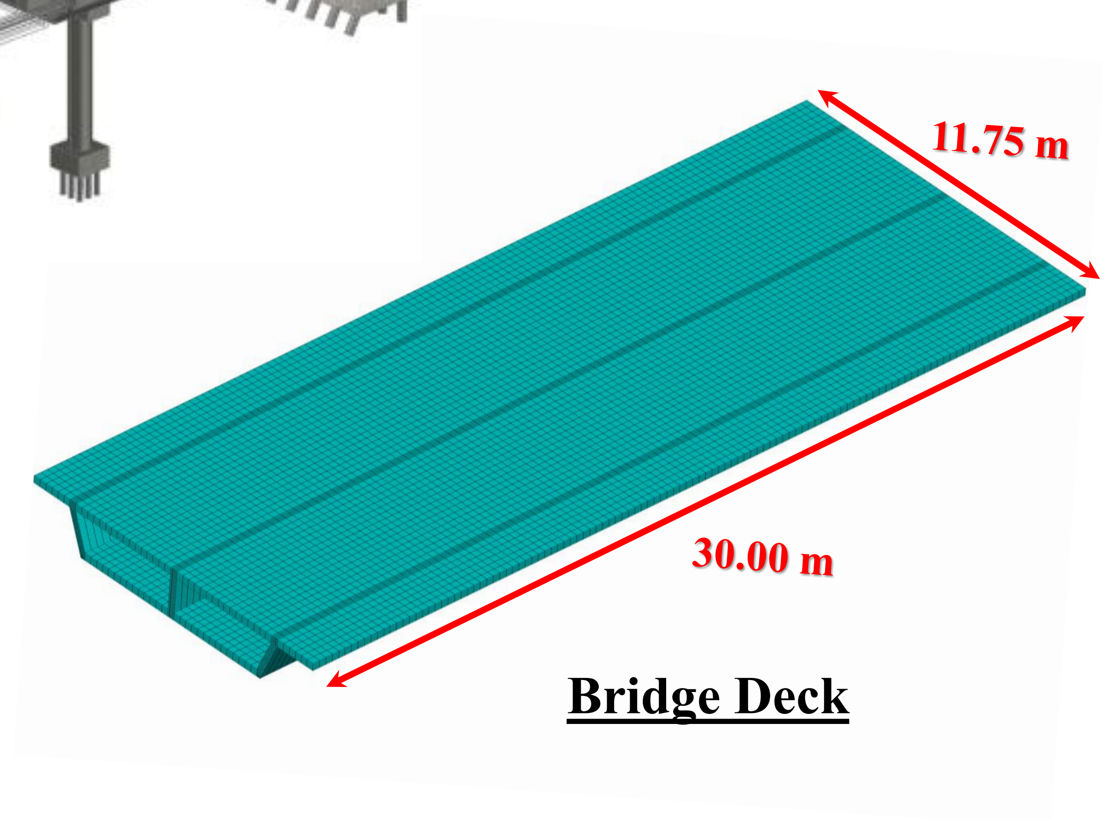
Full-Scale F.E. Models



A two-span bridge with 4 traffic lanes



Bridge Column

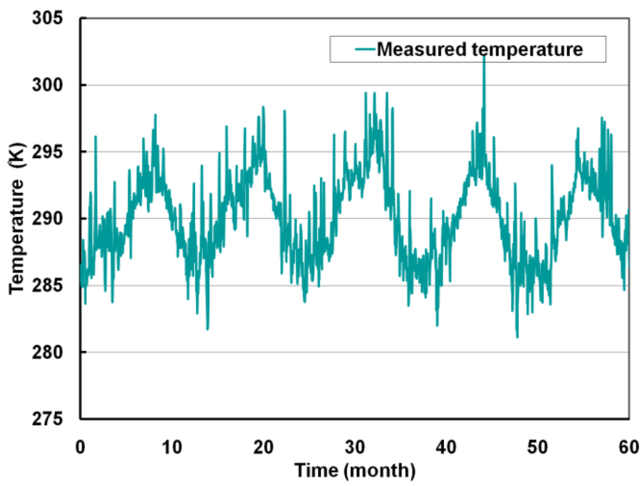


Bridge Deck

Temperature Distribution

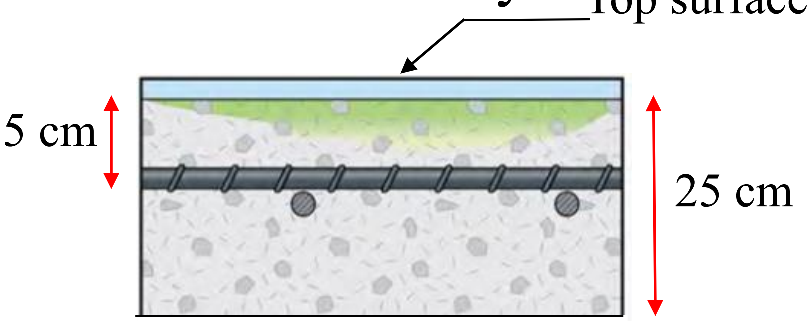
Heat Transfer Mechanism

$$\rho_c c_q \frac{\partial T}{\partial t} = \mathrm{div}(\lambda \vec{\nabla} T)$$



T	Concrete temperature
ρ_c	Concrete density
c_q	Concrete specific heat capacity
λ	Concrete thermal conductivity

Schematic representation of concrete member under study



Boundary Condition

Temperature at top surface: $T_{env} \pm T_{fluc,top} \sin(2\pi t/365)$

Temperature at bottom surface: $T_{env} \pm T_{fluc,bot} \sin(2\pi t/365)$

Moisture Distribution

Humidity Diffusion Process

$$\frac{\partial w_e}{\partial t} = \frac{\partial w_e}{\partial \mathrm{H}}\frac{\partial \mathrm{H}}{\partial t} = \mathrm{div}(D_H \vec{\nabla}(H))$$

H	Relative humidity
w_e	Evaporable water content
D_H	Humidity diffusion coefficient

$$w_e = \frac{CKV_m H}{(1-kH)[1+(C-1)KH]}$$

$$C = \exp\left(\frac{855}{T}\right) \quad K = \frac{\left(1-\frac{1}{n_w}\right)C - 1}{C-1}$$

$$n_w = (2.5 + 15/t_e)(0.33 + 2.2\, w/c)$$

$$V_m = (0.068 - 0.22/t_e)(0.85 + 0.45\, w/c)$$

The parameters C, K and V_m depend on temperature, water/cement ratio and hydration period.

Boundary Condition

Moisture at top surface: $H_{env} \pm H_{fluc,top} \sin(\pi t/365)$

Moisture at bottom surface: $H_{env} \pm H_{fluc,bot} \sin(\pi t/365)$

Profile of Chloride Concentration

Chloride Penetration into Concrete

$$\frac{\partial C_{fc}}{\partial t} = \mathrm{div}\left(\underbrace{D_{cl} w_e \vec{\nabla}(C_{fc})}_{\text{Diffusion}}\right) + \mathrm{div}\left(\underbrace{D_H w_e C_{fc} \vec{\nabla}(H)}_{\text{Convection}}\right)$$

C_{fc}	Concentration of free chloride ions
D_{cl}	Chloride diffusion coefficient

Gradient of concentration is the reason of chloride transport through diffusion process; however, convection refers to chloride movement into concrete within water.

Chloride Penetration

$$D_{cl} = D_{cl,ref} \frac{f_1(T) f_2(t) f_3(H)}{1 + (1/w_e)(\partial C_{bc}/\partial C_{fc})}$$

$$D_H = D_{H,ref} \frac{g_1(T) g_2(t) g_3(H)}{1 + (1/w_e)(\partial C_{bc}/\partial C_{fc})}$$

$D_{cl,ref}$ $D_{H,ref}$	Reference diffusion coefficients
$f_1(T)$ $g_1(T)$	Temperature modification factors
$f_2(t)$ $g_2(t)$	Aging modification factors
$f_3(H)$ $g_3(H)$	Humidity modification factors
α_L β_L	Binding coefficients

$(\partial C_{bc}/\partial C_{fc})$ represents the binding capacity of cementitious material

- Linear
- Langmuir
- Freundlich

$$C_{bc} = \frac{\alpha_L C_{fc}}{1 + \beta_L C_{fc}}$$

Climate Change Scenarios

Scenarios

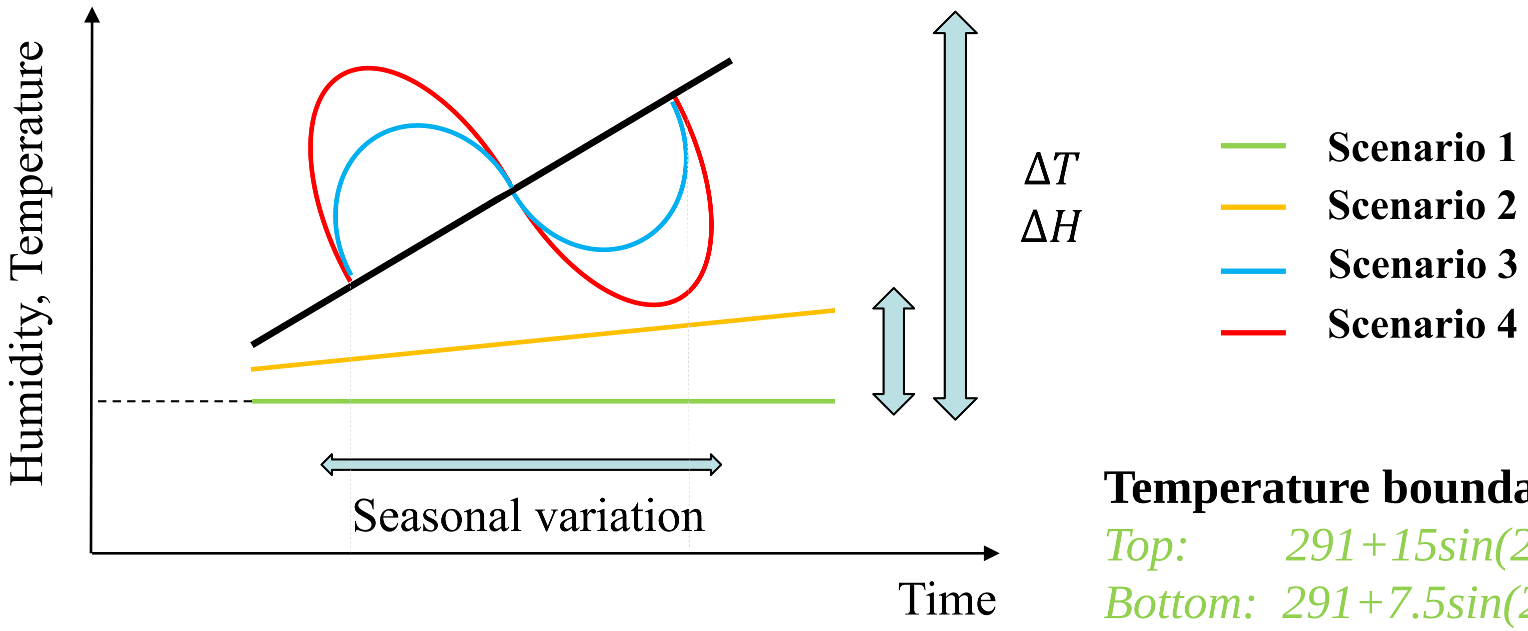
1. Without climate change: $\Delta T = \Delta H = 0$

2. Expected scenario: $\Delta T = 2.5, \Delta H = 0.05$
Use of alternative and fossil sources of energy, birthrates follow the current patterns and there is no extensive employment of clean technology.

3. Pessimistic scenario: $\Delta T = 6.5, \Delta H = 0.10$
Vast utilization of fossil sources of energy, appreciable growth of population and there are no policies to develop and extend the use of clean technologies.

4. Extremely pessimistic scenario: $\Delta T = 6.5, \Delta H = 0.10$
The trend of temperature and humidity is similar to the pessimistic scenario; however, the effect of climate change on ecosystem (hotter and colder days) is considered.

Climate Change Scenarios



Surface chloride (kg/m³)

[1.0-3.0] [1.5-4.0] [2.0-7.0] [2.0-7.0]

Humidity boundary conditions

$0.65+0.13\sin(2\pi t/365)$

$0.65+0.13\sin(2\pi t/365)+0.05$

$0.65+0.13\sin(2\pi t/365)+0.10$

$0.65+0.13\sin(2\pi t/365)+0.10$

Temperature boundary conditions

Top: $291+15\sin(2\pi t/365)$

Bottom: $291+7.5\sin(2\pi t/365)$

Top: $291+15\sin(2\pi t/365)+2.5$

Bottom: $291+7.5\sin(2\pi t/365)+2.5$

Top: $291+15\sin(2\pi t/365)+6.5$

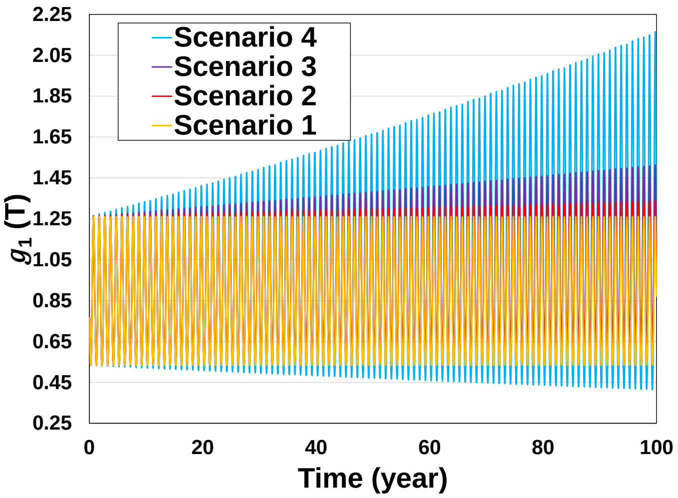
Bottom: $291+7.5\sin(2\pi t/365)+6.5$

Top: $291+30\sin(2\pi t/365)+6.5$

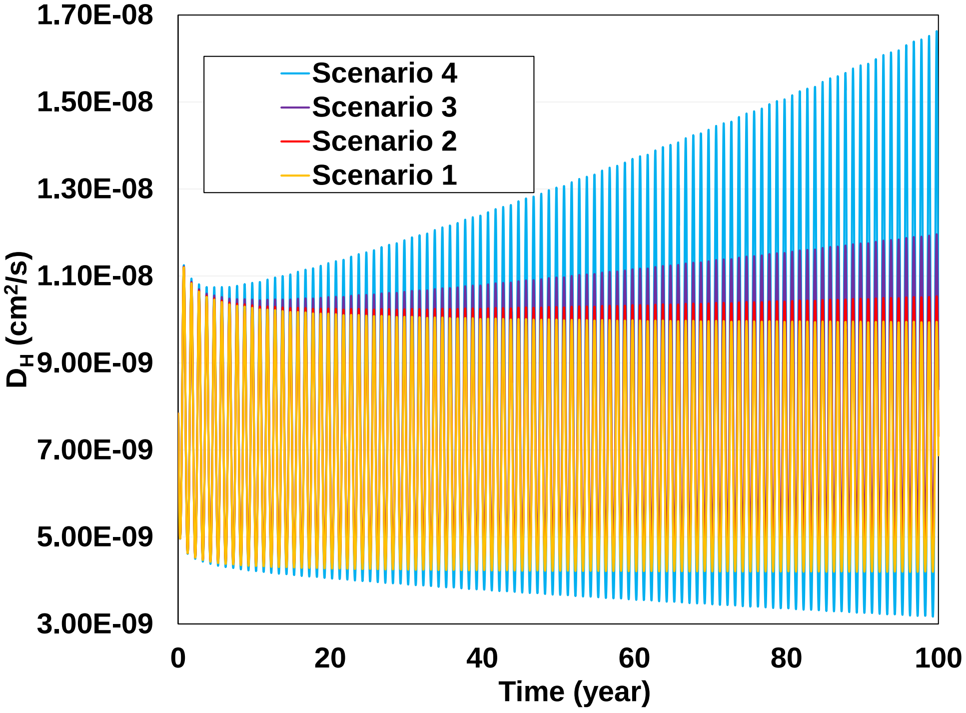
Bottom: $291+15\sin(2\pi t/365)+6.5$

Humidity Parameters

- Temperature modification factor

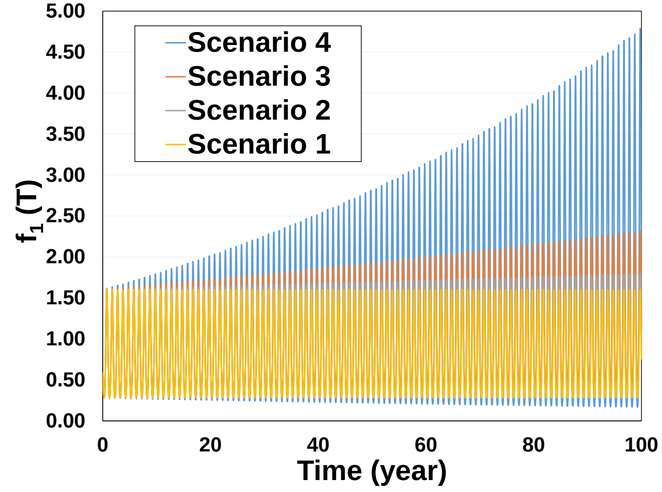


- Humidity diffusion coefficient

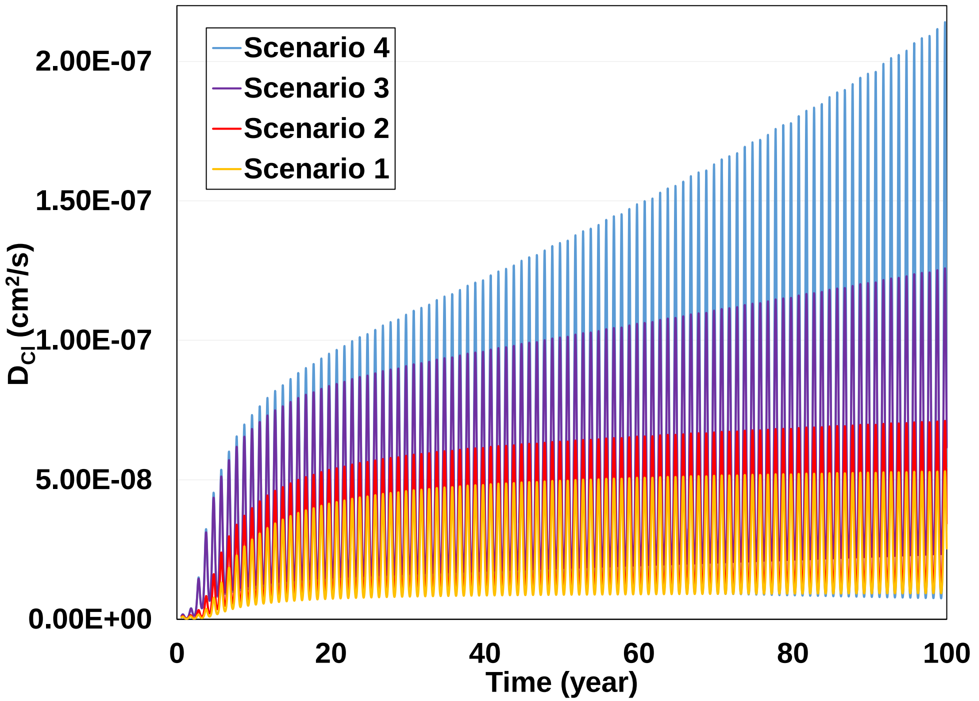


Chloride Parameters

- Temperature modification factor

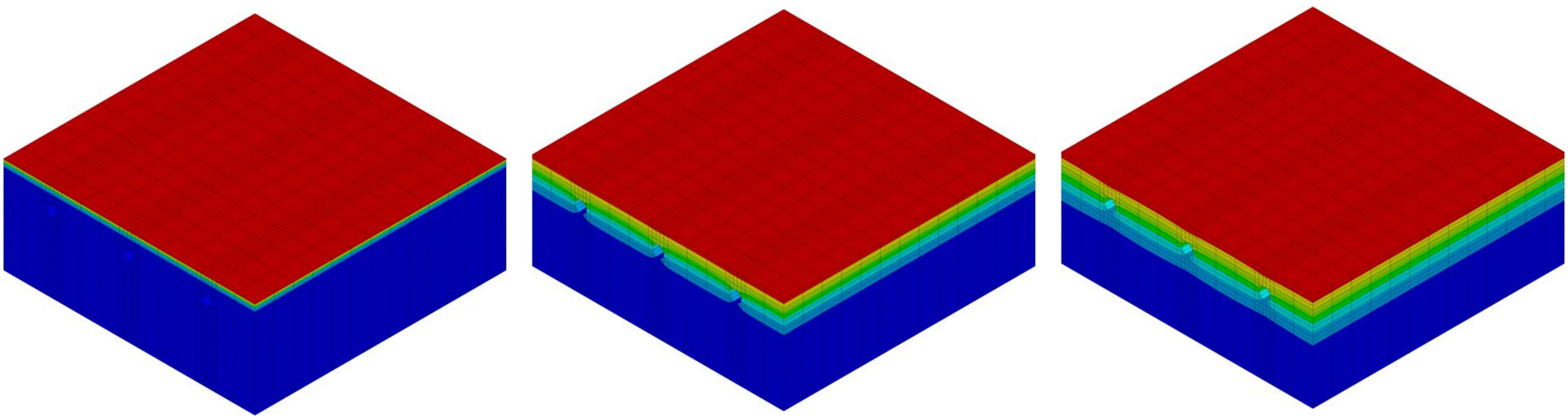


- Chloride diffusion coefficient



Chloride Penetration

Extent of chloride penetration into the concrete over a 50-year time period



After 1 year → **After 25 years** → **After 50 years**

Condition States

Stages of structural deterioration:

- Corrosion initiation
- Crack initiation
- Crack propagation

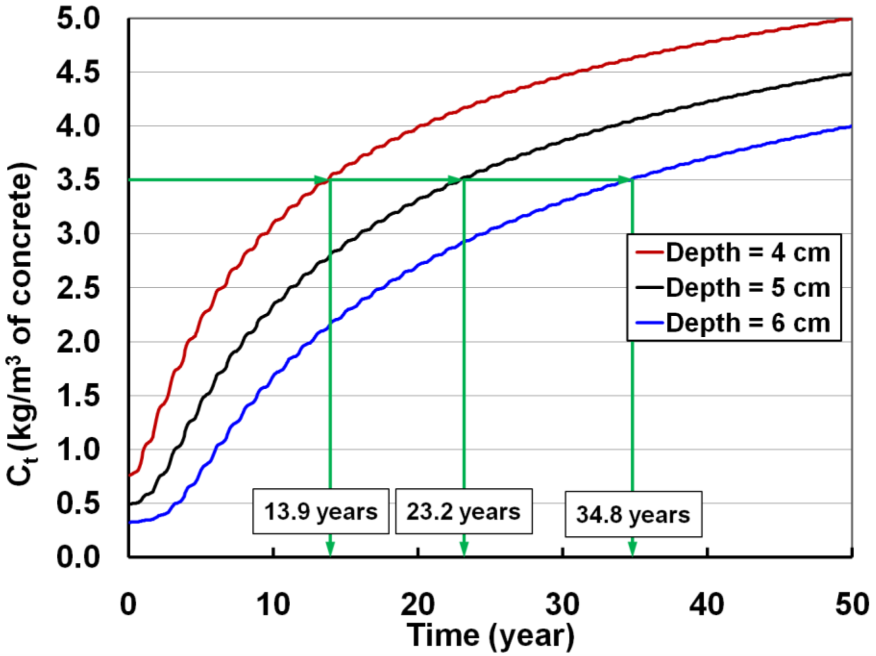
Corrosion initiation time

$$Cl_t(t_{ini}, d_c) = Cl_{critical}$$

Measure for evaluation of extent of structural deterioration

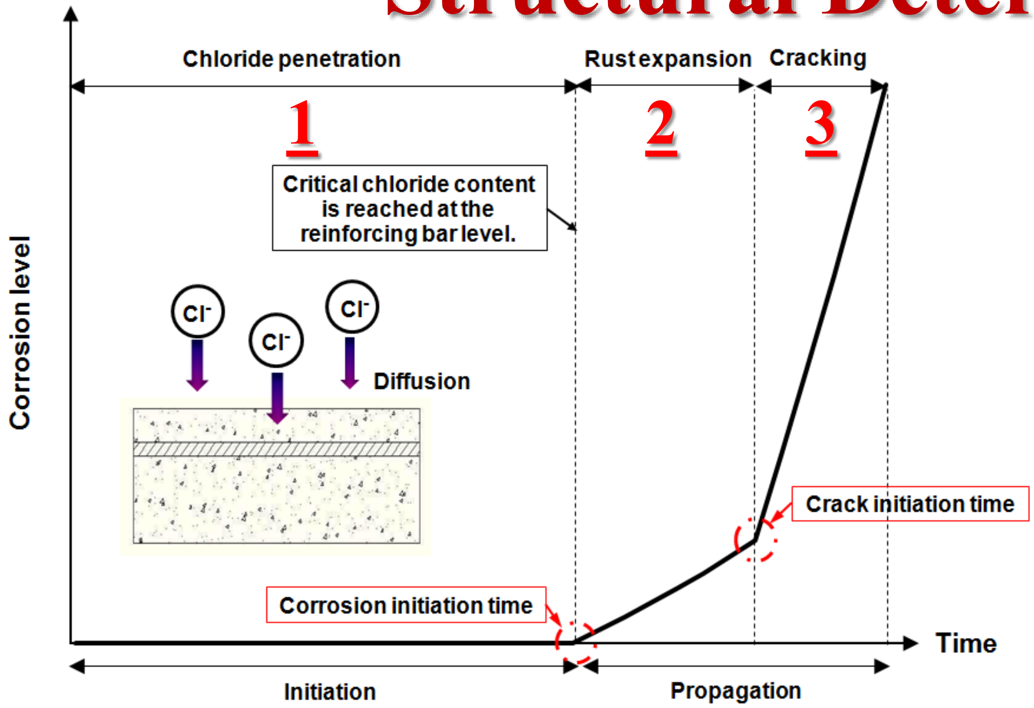
⇩

Condition State



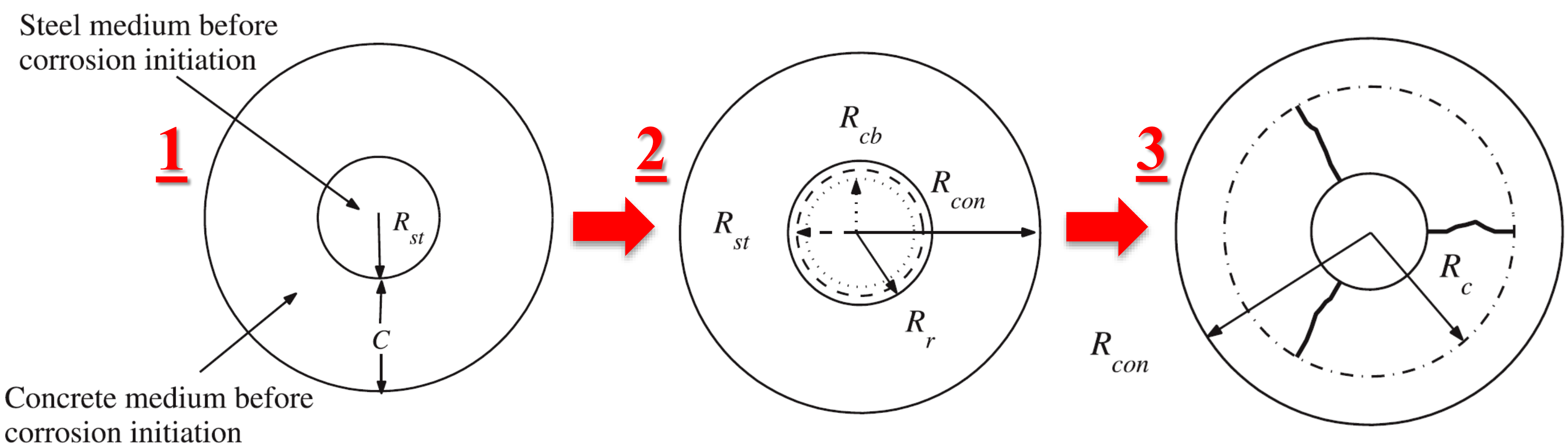
Condition State	Description
1	$0.0 \leq [Cl] \leq 0.5$ kg/m^3 (new or near new)
2	$0.5 \leq [Cl] \leq 1.0$ kg/m^3
3	$1.0 \leq [Cl] \leq 2.0$ kg/m^3
4	$2.0 \leq [Cl] \leq 5.0$ kg/m^3
5	$5.0 \leq [Cl]$ kg/m^3 (susceptible to failure)

Structural Deterioration



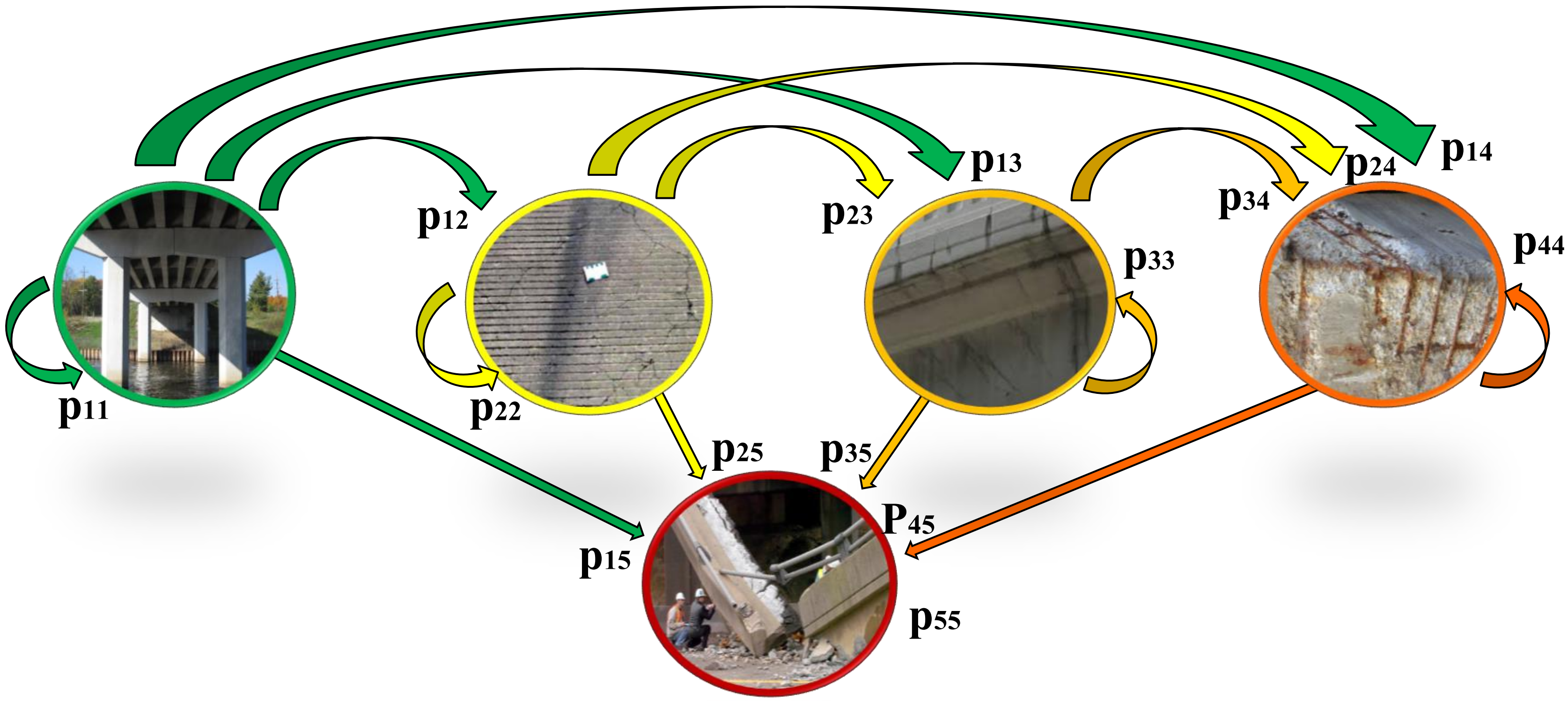
Deterioration process:

- Corrosion initiation
  - Diffusion of chloride
  - Depassivation
- Corrosion propagation
  - Rust expansion
  - Cracking



Condition States

Condition State	1	2	3	4	Beyond
Description	New (good condition)	Minor problems	Major problems	Beyond the serviceability	Failure (collapse)



Bridge Management System

- There are several uncertain factors contributing to predict the future condition of infrastructure components.
- To include various sources of uncertainty, Moving Ahead for Progress in the 21st Century Act (MAP-21) requires U.S. transportation agencies to integrate "**risk**" into their existing asset management plans.
- Risk management greatly helps the transportation agencies to anticipate the possible consequences of system failure and develop necessary strategies to maintain the system in an acceptable level of performance during both **normal** and **extreme** conditions.
- The maintenance strategy is achieved based on cost analysis. MAP-21 encourages the use of LCCA for the evaluation of all major investment decisions.

MAP-21
TRANSPORTATION ALTERNATIVES PROGRAM

Life-Cycle Cost Analysis

Life-Cycle Cost (LCC):

$$\text{LCC} = C_c + [C_{IN} + C_M + C_M^u] + C_{sf} + C_{sf}^u$$

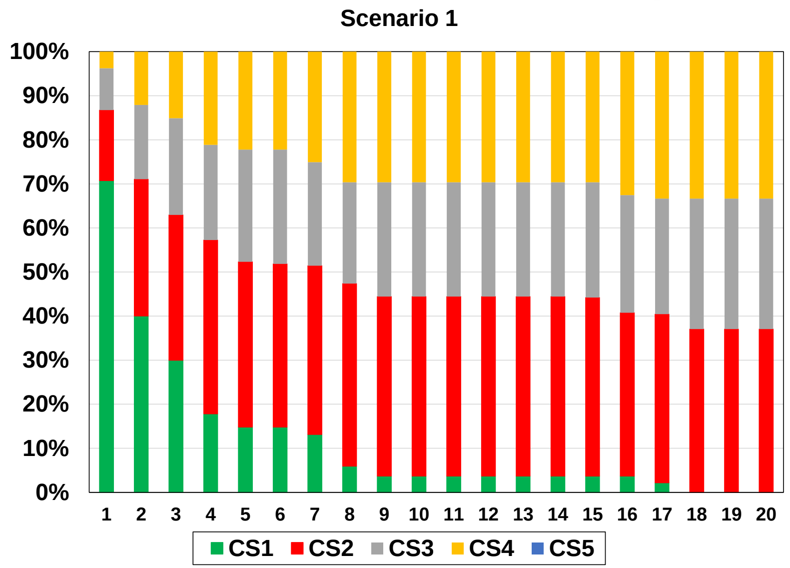
$$C_{IN} = \sum_{i=1}^{100} Sa(i\Delta t)$$

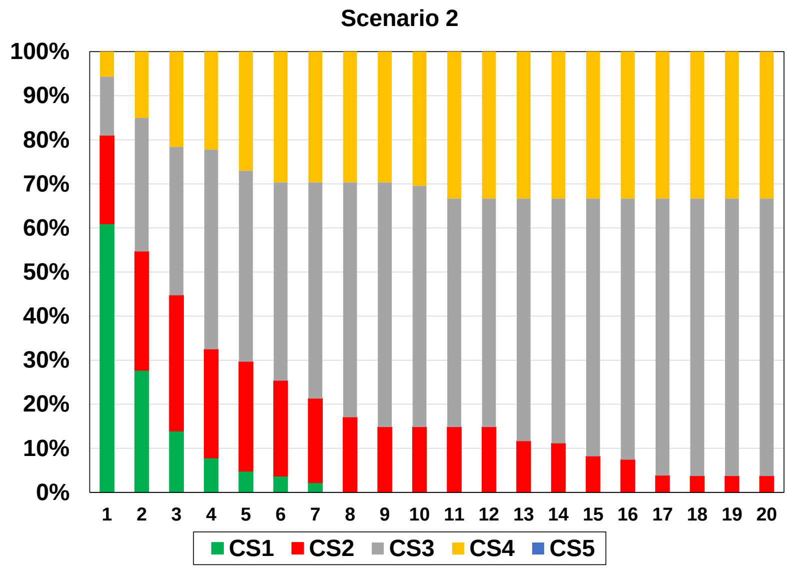
$$C_M = \sum_{i=1}^{100} Ma(i\Delta t) \qquad C_M^u = \sum_{i=1}^{100} t_m b_m u a(i\Delta t)$$

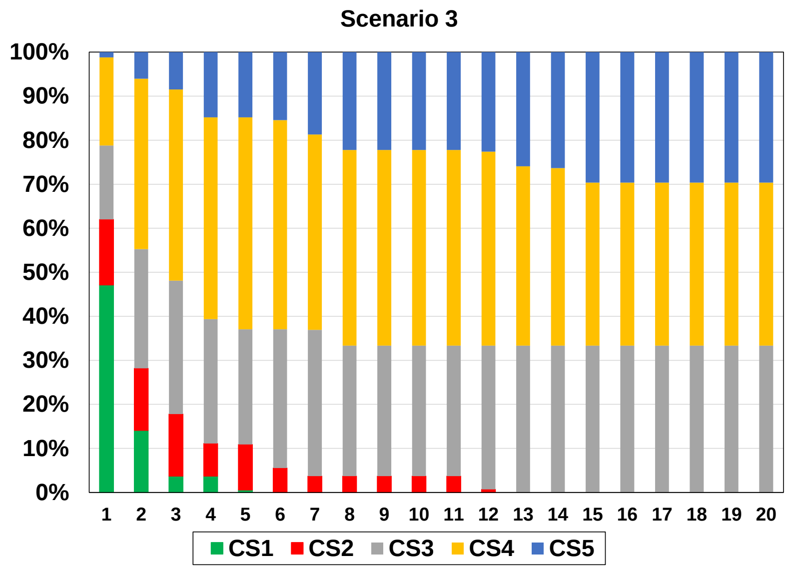
$$C_{sf} = \sum_{i=1}^{100} C\Delta p a(i\Delta t) \qquad C_{sf}^u = \sum_{i=1}^{100} t_{sf} b_{sf} u \Delta p a(i\Delta t)$$

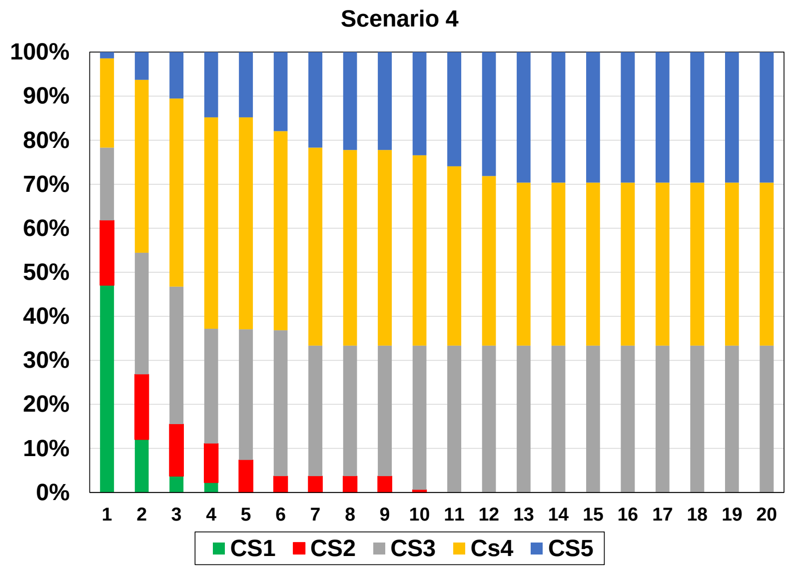
C_c	Initial construction cost	t_m	Maintenance duration
C_{IN}	Inspection cost	b_m	Usage disruption
C_M	Maintenance cost	u	Unit user cost
C_M^u	Indirect maintenance cost	C	Repair cost
C_{sf}	Failure cost	Δp	Probability of failure
C_{sf}^u	Indirect failure cost	t_{sf}	Repair duration
S, M	Cost of inspection, maintenance	b_{sf}	Usage disruption
a	Discount factor	i	Interest rate

Life-Cycle Cost Analysis



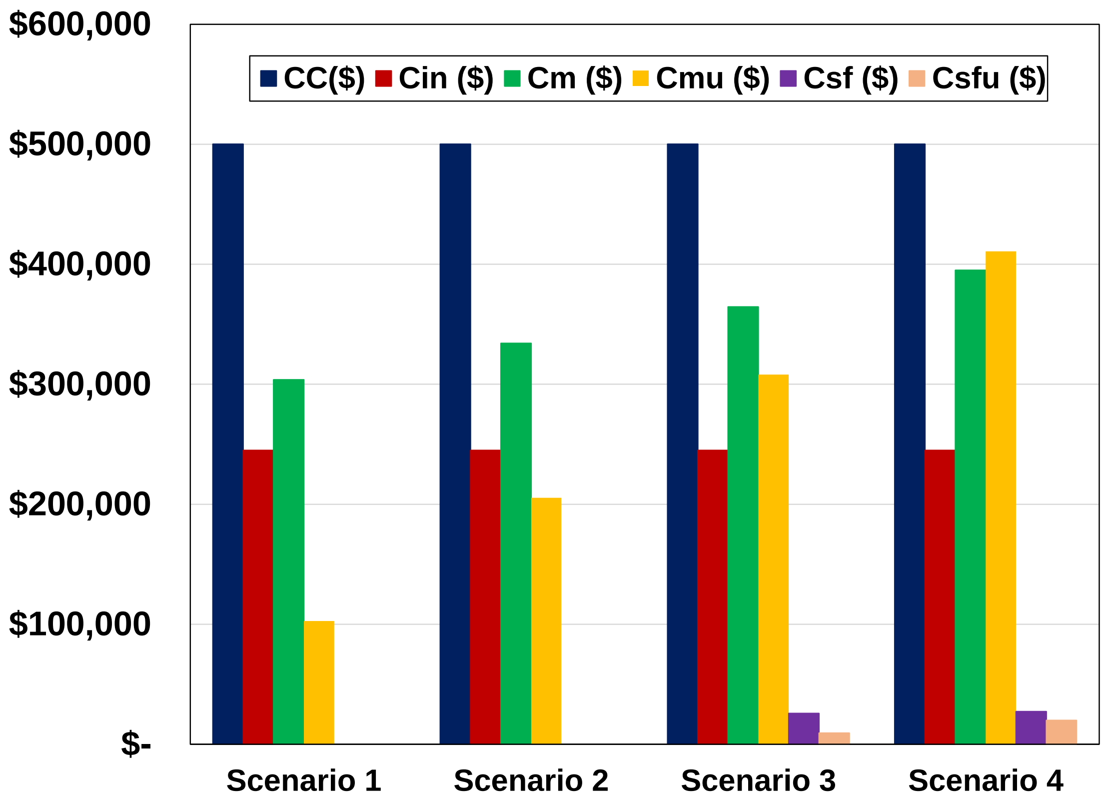






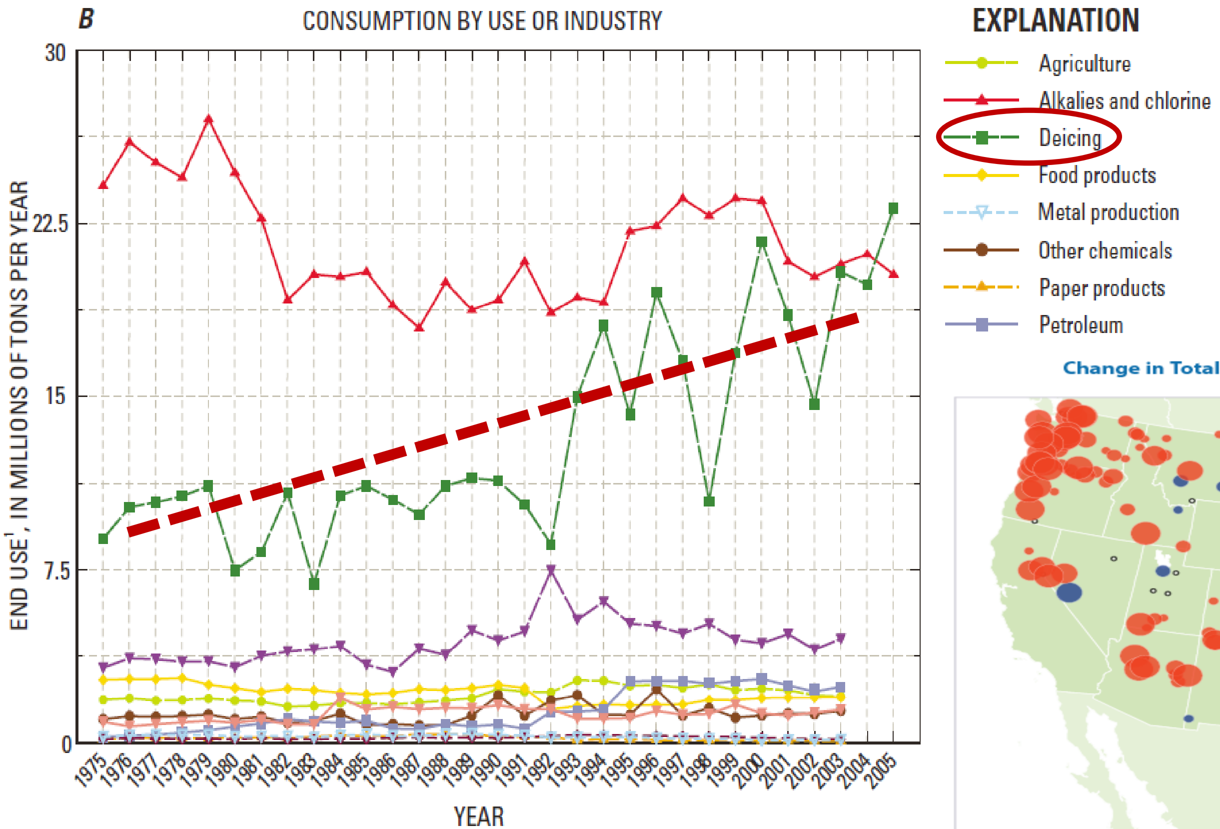
Cost Comparison

Life cycle cost estimated for the four climate scenarios:



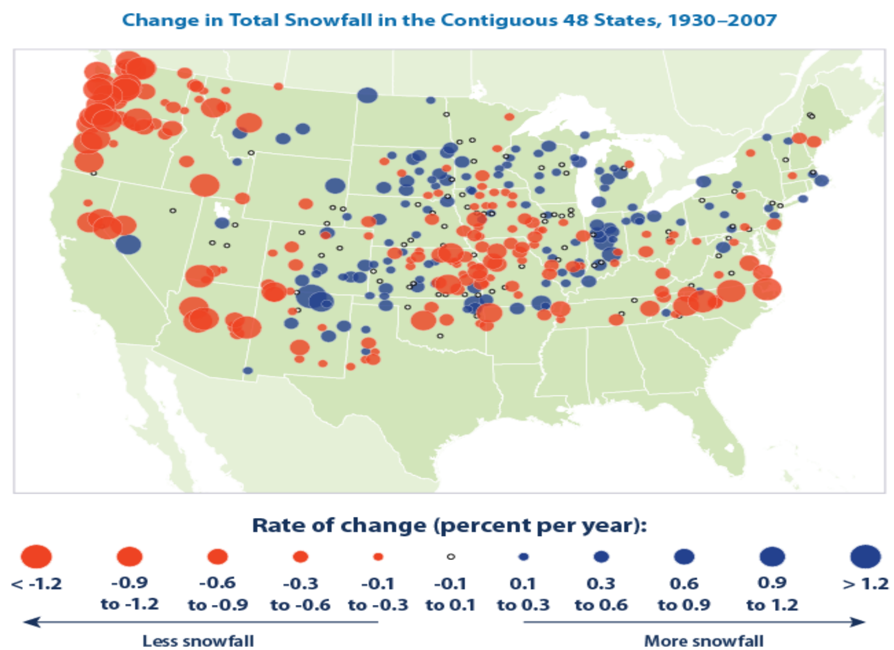
Future Work

Salt Consumption



Finday & Kelly (2011)

Snowfall Change (1930-2007) - EPA



Conclusions

- Long-term durability and performance of transportation infrastructure components are affected by deterioration processes. It was shown that such processes are influenced by weather conditions, including ambient temperature, humidity, and aggressive environment.
- The environmental stressors are modeled using a comprehensive computational framework. The effects of time-dependent parameters that capture the climate change impact are captured.
- By introducing various climate scenarios, the extent of structural degradation is predicted during the design life cycle.
- The total life cycle cost is calculated to further examine the potential impact of weather-related events on the management of civil infrastructure components.

Acknowledgement

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Thank you!

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- Khatami, D., **Shafei, B.**, and Smadi, O. (2016) "*Management of bridges under aging mechanisms and extreme events: A Risk-Based Approach*", Transportation Research Record Journal, Paper 16-5930.
- **Shafei, B.** and Alipour, A. (2015) "*Application of large-scale non-Gaussian stochastic fields for the study of corrosion-induced structural deterioration*", Journal of Engineering Structures, 88, pp. 262-276.
- Alipour, A., **Shafei, B.**, and Shinozuka, M. (2013) "*Capacity loss evaluation of reinforced concrete bridges located in extreme chloride-laden environments*", Journal of Structure and Infrastructure Engineering, 9(1), pp. 8-27.