Multiway Analysis of Bridge Structural Types in the National Bridge Inventory (NBI)

A Tensor Decomposition Approach

By

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(IEEE Big Data Conference -10/27/2014)

Presentation Outline

- Introduction
- Basic Tensor Concepts
- Analysis & Results
- Conclusion & Recommendations

INTRODUCTION

National Bridge Inventory (NBI)

- Largest database of bridge data in the world[1]
- Information on >600,000 bridges
- Owned and operated by the Federal Highway Administration (FHWA)
- Status of a bridge:
  - not deficient;
  - structurally deficient; and
  - functionally obsolete
- Basis for determining eligibility for Federal Bridge Funding

Structurally Deficient Bridges

- Structurally deficient bridges have load carrying members in poor condition or significantly below design standards
- Repair, rehabilitation or replacement required
- In the US, 1 in 9 bridges is structurally deficient
- Laid end to end, structurally deficient bridges will span from DC to Denver[2]

Sherman-Minton Bridge*

* http://www.transportationissuesdaily.com/wp-content/uploads/2011/10/Sherman-Minton-Bridge.jpg

- Effective use of bridge rehabilitation and replacement funding
- Need to understand deterioration patterns of bridges under varying loading and environmental conditions
- NBI can serve as a major resource

Focus of Research

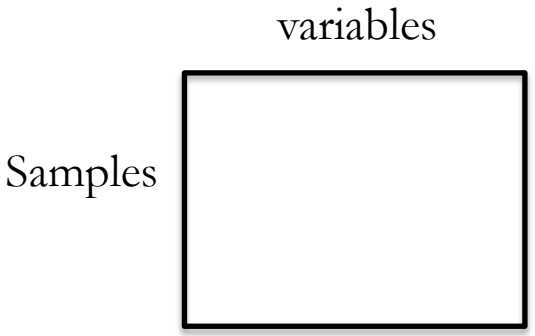
- Analysis of deterioration trends of specific bridge deck structural types in the US

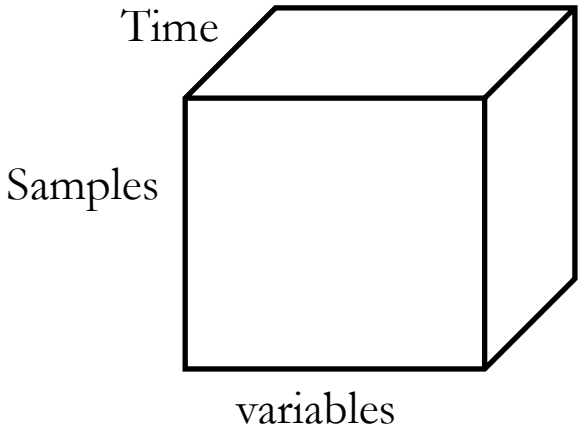
- Tensor Decomposition

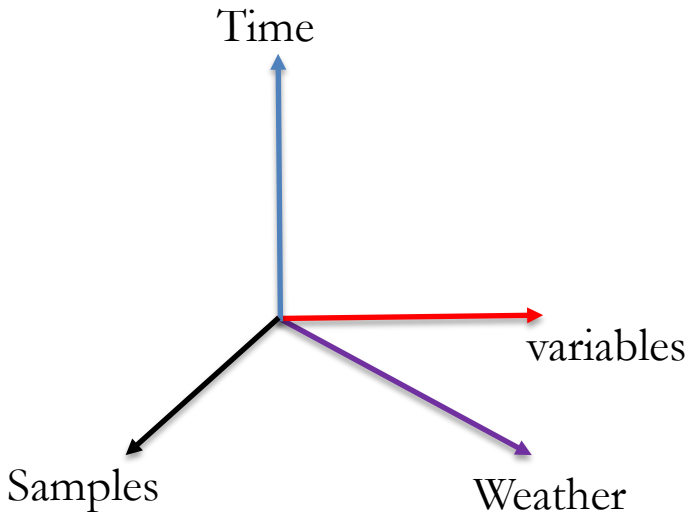
BASIC TENSOR CONCEPTS

What are Tensors?

- Generalizations of scalars, vectors and matrices



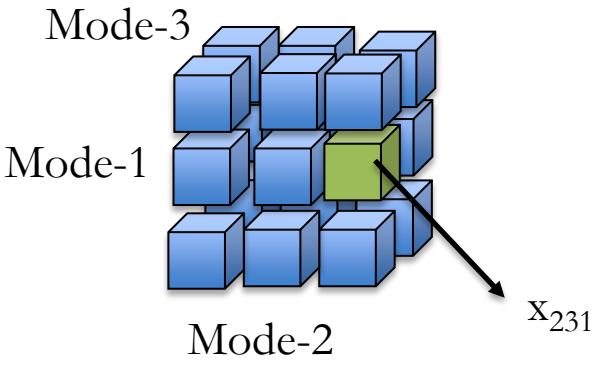




Why Multiway Data Analysis?

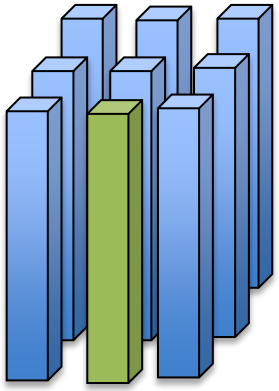
- Multiway data is everywhere
- Capture variation in dataset while preserving multidimensional nature of data
- Reveal hidden patterns in data

Typical 3D dataset



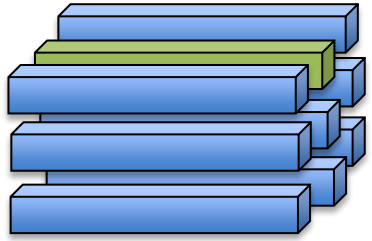
$\underline{\mathbf{X}}$

Subarrays



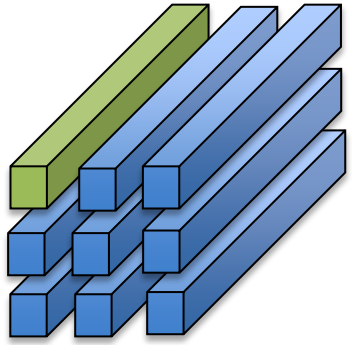
Mode-1 Fiber

$x_{:21}$



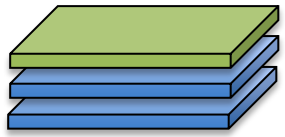
Mode-2 Fiber

$x_{1:2}$



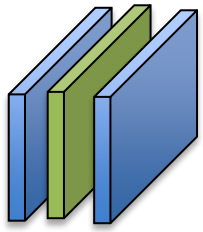
Mode-3 Fiber

$X_{11:}$



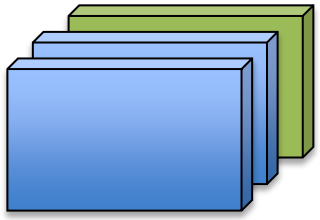
Horizontal slice

$X_{1::}$



Lateral slice

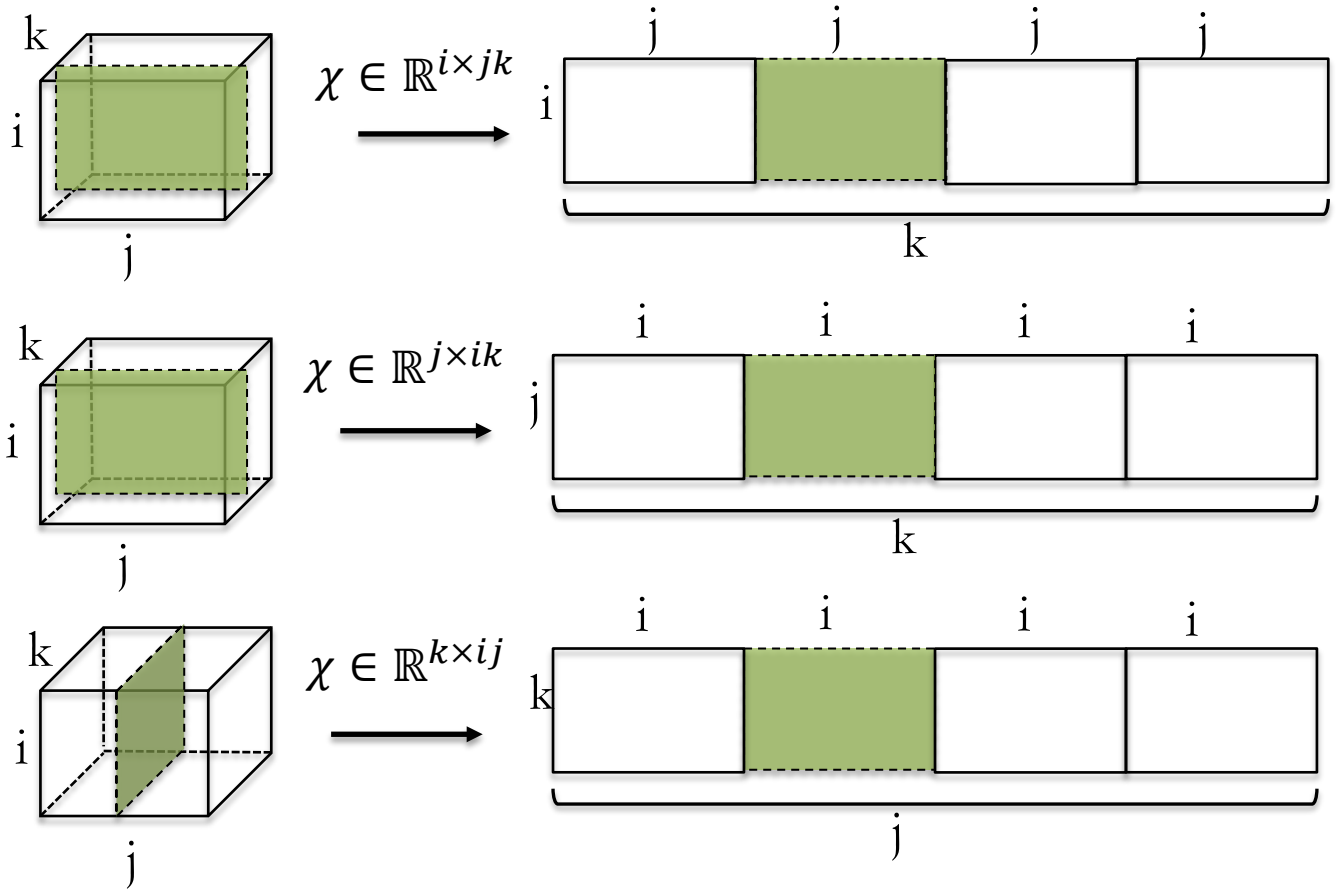
$X_{:2:}$



Frontal slice

$X_{::3}$

Matricization (Unfolding)



Summation: $\boldsymbol{\mathcal{A}} + \boldsymbol{\mathcal{B}} = \boldsymbol{\mathcal{C}}$,
where $\boldsymbol{\mathcal{C}}_{ijk} = a_{ijk} + b_{ijk}$

Outer Product: $\boldsymbol{\mathcal{X}} = \boldsymbol{a} \circ \boldsymbol{b} \circ \boldsymbol{c}$
s.t. $x_{ijk} = a_i b_j c_k$

Khatri-Rao Product: $\boldsymbol{P}^{I \times J} \odot \boldsymbol{Q}^{K \times J} = \boldsymbol{R}^{IK \times J}$

Kronecker Product: $\boldsymbol{P}^{I \times J} \otimes \boldsymbol{Q}^{K \times L} = \boldsymbol{R}^{IK \times JL}$

Hadamard Product: $\boldsymbol{P}^{I \times J} \circledast \boldsymbol{Q}^{I \times J} = \boldsymbol{R}^{I \times J}$

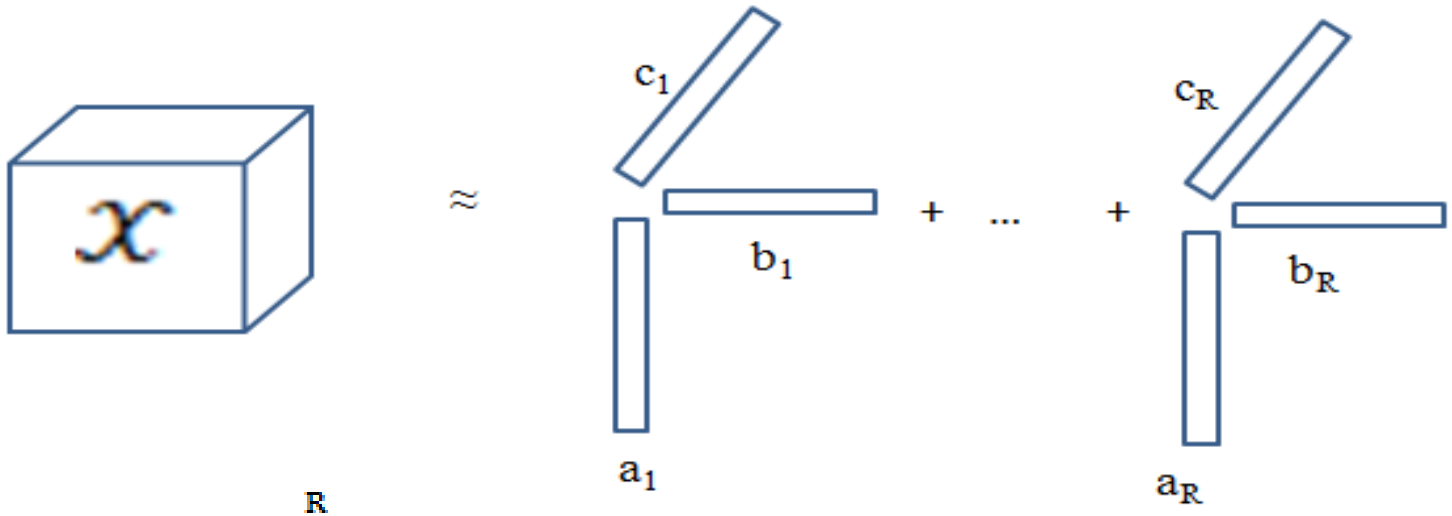
Tensor Decomposition

- Reducing data to lower-order forms for analysis (classification, prediction, clustering)

- 2 main approaches
  - Canonical decomposition/Parallel Factors (CANDECOMP/PARAFAC; **CP**)
  - **Tucker decomposition**

The CP Decomposition

- Canonical Decomposition/ Parallel Factors



$$\mathcal{X} = \sum_{r=1}^{R} a_r \circ b_r \circ c_r$$

a_i, b_i and c_i - factor loadings

R- number of components

Rank of a tensor=min (R) required to approximate **X**

Choosing the appropriate CP model

- Alternating Least Squares Approach (ALS)

$$min_{\hat{x}} \|\mathcal{X} - \hat{\mathcal{X}}\|$$

Where $\hat{\mathcal{X}}$ is the PARAFAC model

- % Variance Explained

- Core Consistency Diagnostic (CORCONDIAG)
  - High CORCONDIAG → stable model
  - Low CORCONDIAG → invalid and/or problematic model

ANALYSIS & RESULTS

Structural Deterioration Rate

$$SD_{i,j,k} = \frac{n_{i,j,k}}{\sum_j N_{i,j,k}}$$

Where:

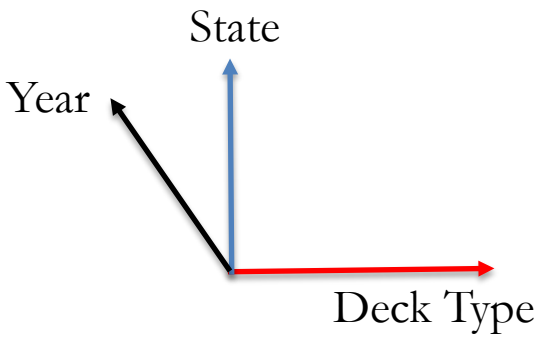
$SD_{i,j,k}$=structural deterioration rate in state i of structure type j in year k

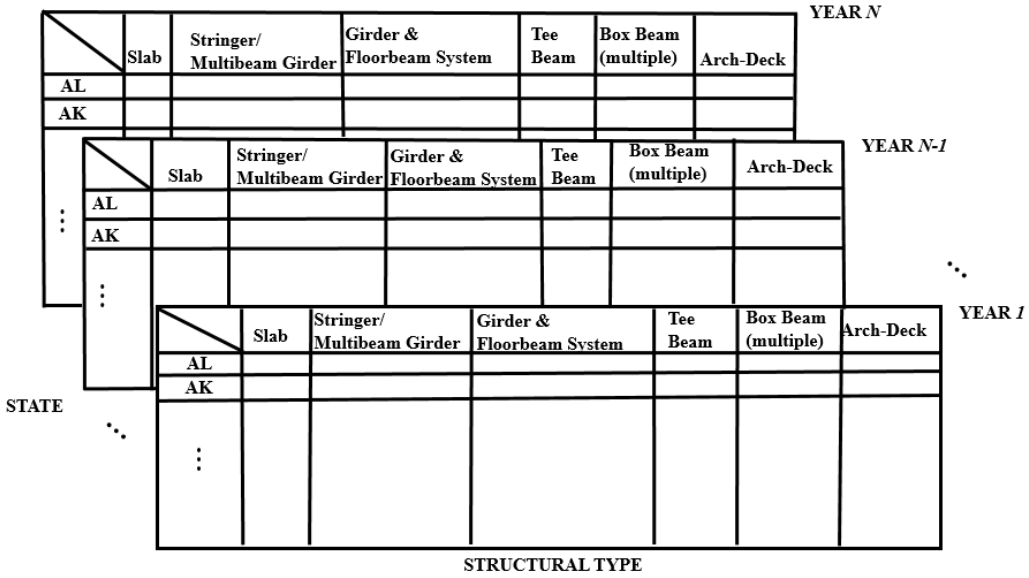
$n_{i,j,k}$=number of structurally deficient bridges in state i of structure type j in year k

$N_{i,j,k}$=number of bridges in state i of structure type j in year k

Dataset

- NBI database (1992-2013)
- Structurally deficient bridge design types by state



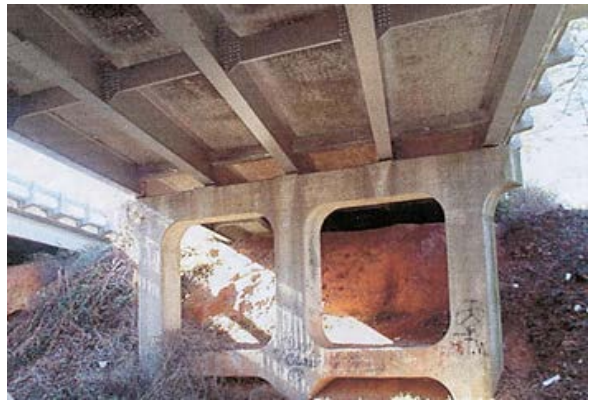


Multidimensional Dataset for analysis

Selected Bridge Design Types

Girder and Floorbeam[4]

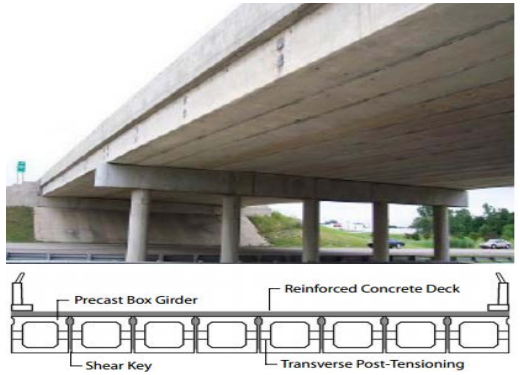
Slab[5]



Stringer/Multibeam[6]

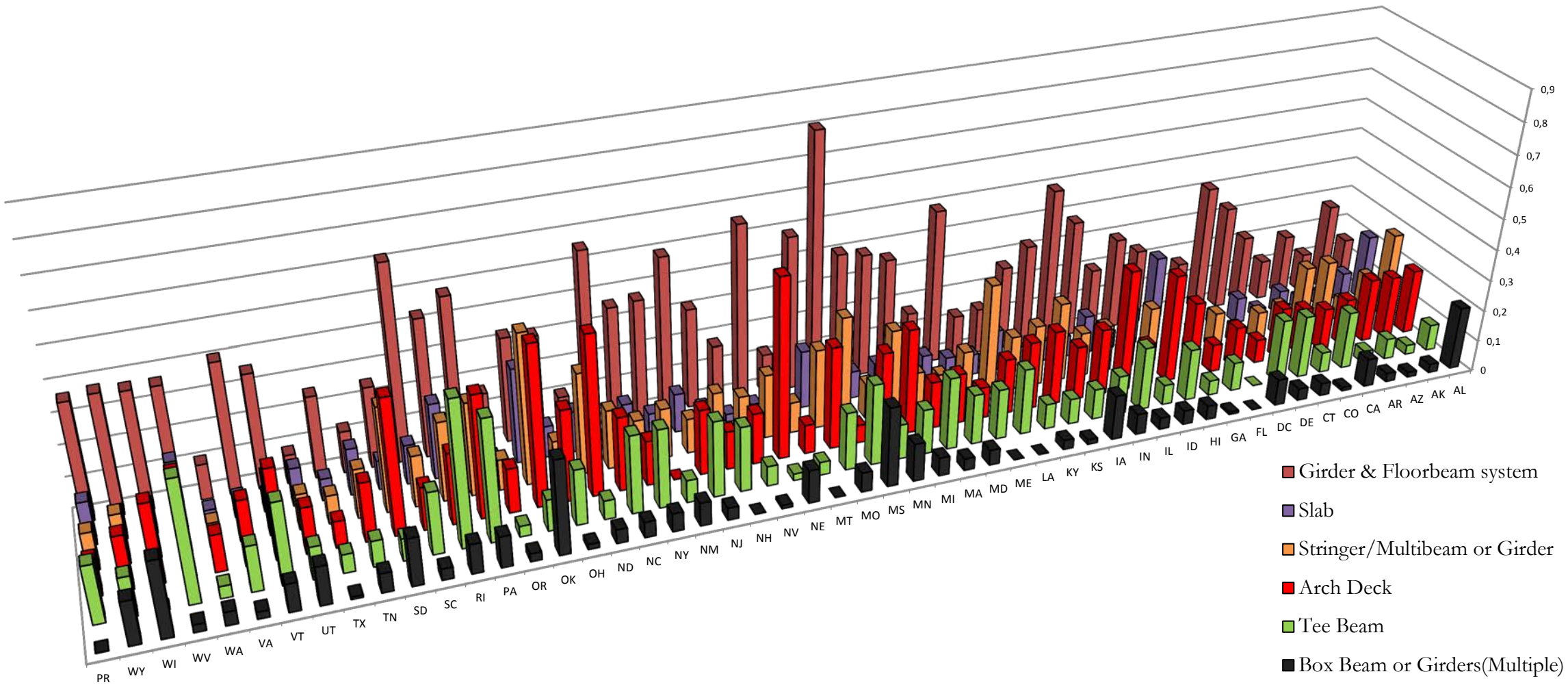
Arch Deck[7]

Tee Beam[8]

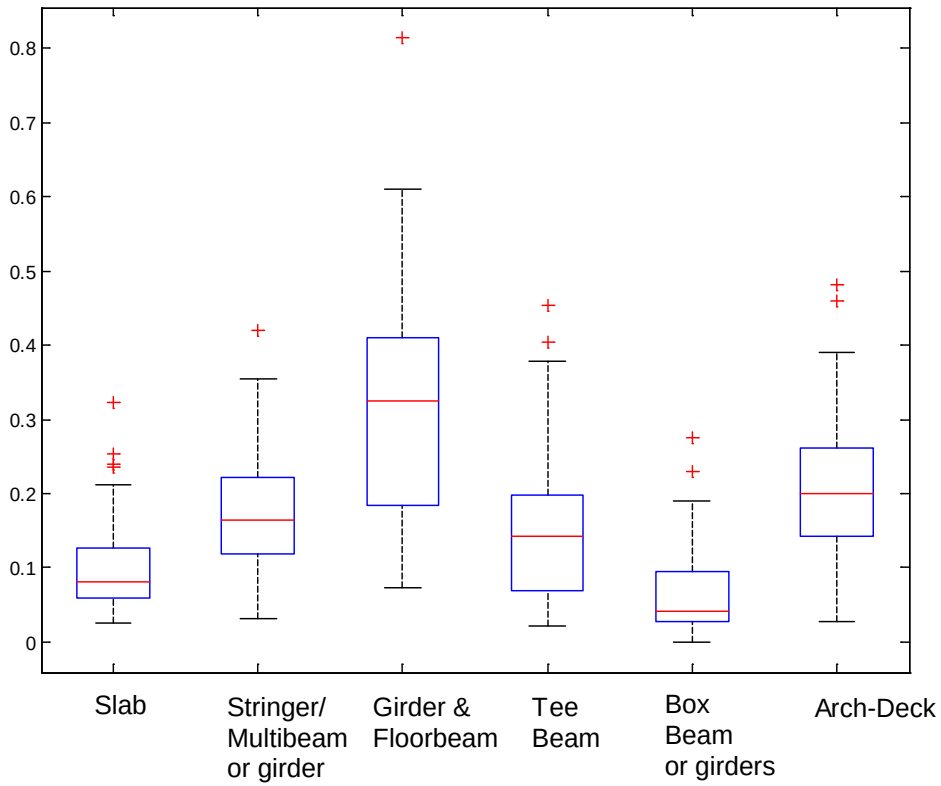


Box Beam[9]

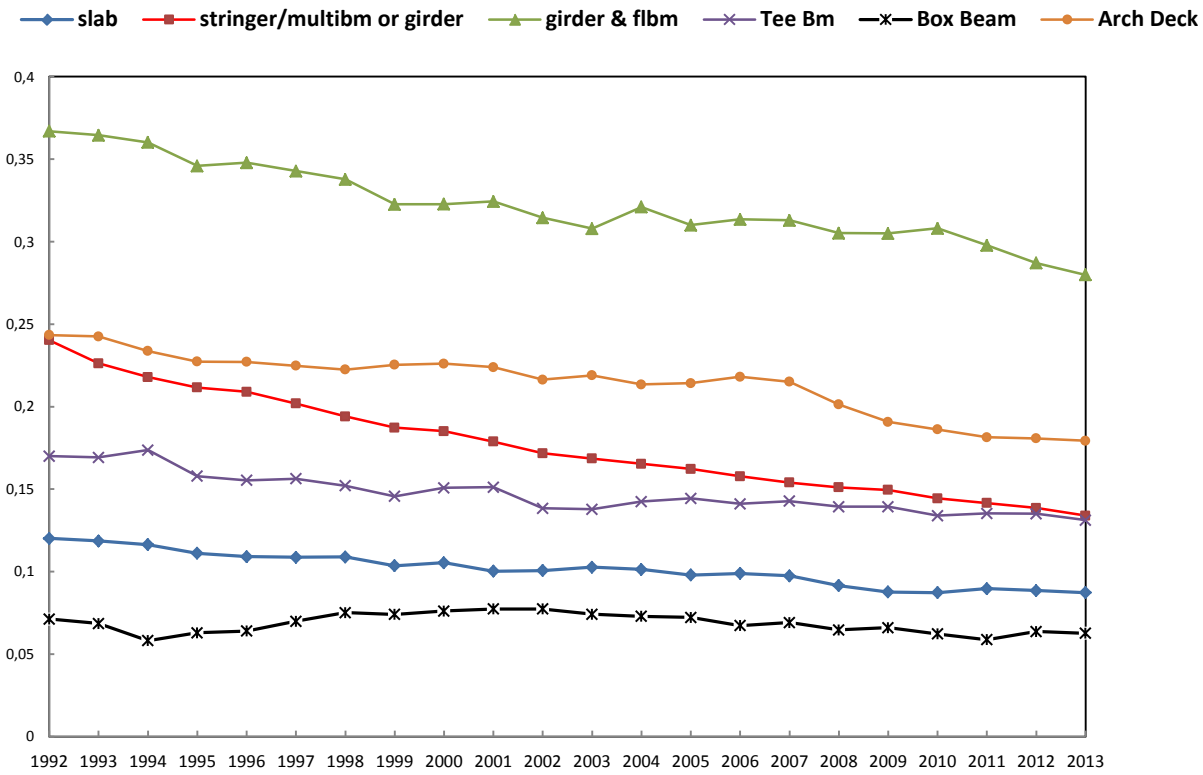
3D visualization



Exploration of NBI structure type data



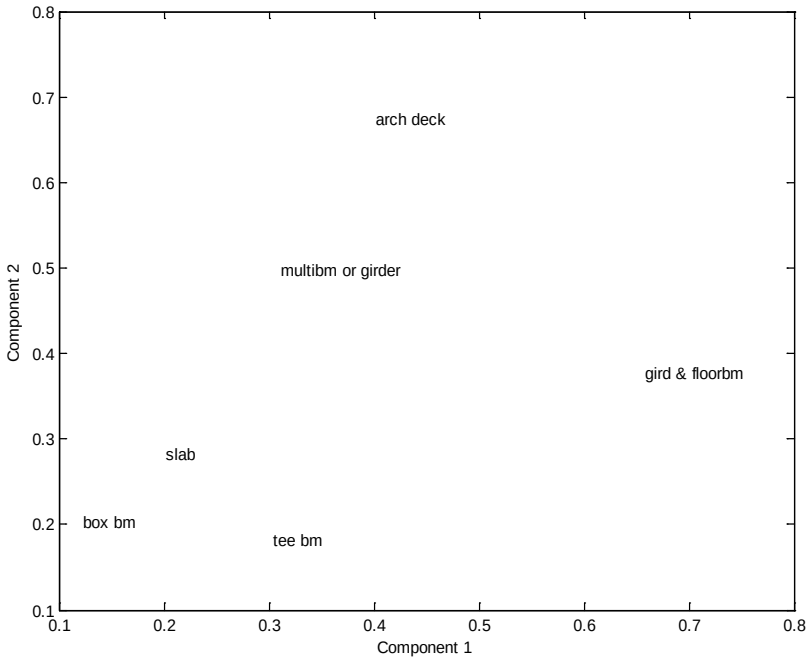
Box plot of mean SD rates over 22 years



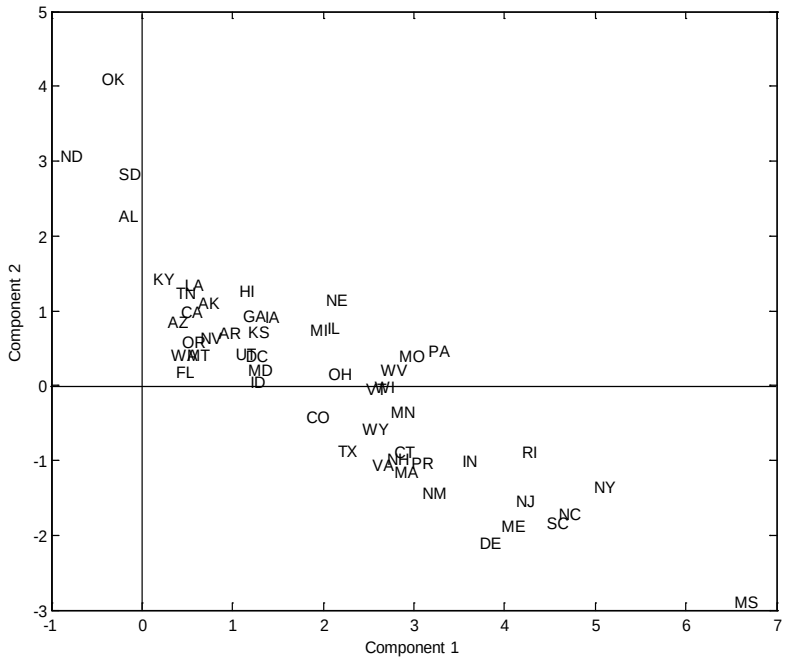
SD rate trends for structural types

Decomposition plots

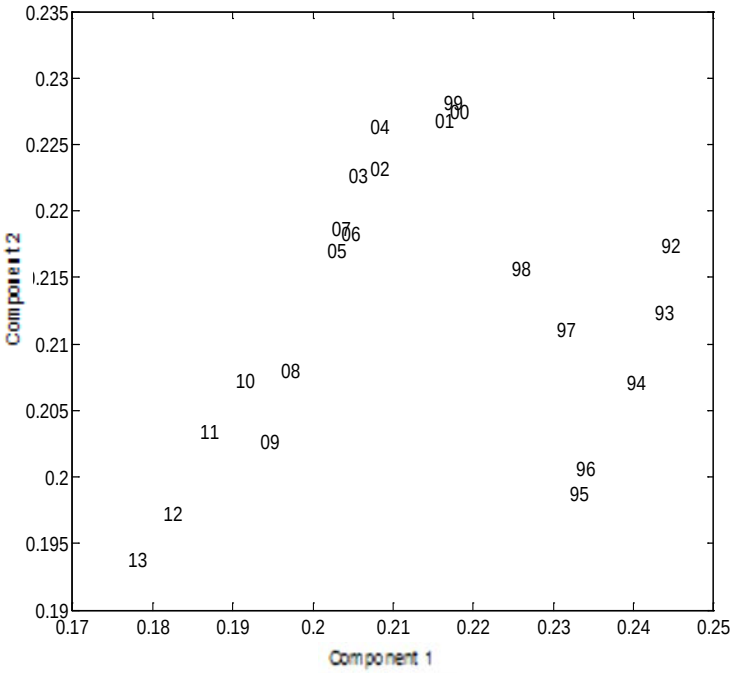
- 2 component PARAFAC model was fitted to the data
- Variance explained= 90.15%



Loading plot for Structure types



Loading plot for States



Loading plot for years

Conclusion & Recommendations

- Demonstrates tensor decomposition as a knowledge discovery tool that has applications in bridge industry
- Detailed analysis which incorporates other deterioration factors such as age, ADT, and geographical location.
- Prediction

References

(1) Wu N., Chase S. An Exploratory Data Analysis of National Bridge Inventory. Mid-Atlantic Universities Transportation Center (MAUTC). UVA-2009-03. May 2010

(2) Davis S.L., Goldberg D. The Fix We're in For: The State of Our Nation's Bridges 2013. Transportation for America. June 2013

(3) Steel Girder & Floorbeam. http://www.ncdot.gov/_graphics/site_graphics/projects_ncbridges_hb_t_steelgirder01.jpg. Accessed:10/21/2014

(4) Slab bridges. http://www.ncdot.gov/_graphics/site_graphics/projects_ncbridges_hb_t_conslab01.jpg. Accessed:10/21/2014

(5) Steel stringer or multibeam. http://www.ncdot.gov/projects/ncbridges/historic/types/?p=13#types. Accessed:10/21/2014

(6) Arch Deck. http://www.asce.org/CEMagazine/Article.aspx?id=25769811288#.VEbR8PldWL0. Accessed:10/21/2014

(7) Tee Beam. http://www.ncdot.gov/_graphics/site_graphics/projects_ncbridges_hb_t_teebeam01.jpg. Accessed:10/21/2014

(8) Box Beam bridge. https://www.michigan.gov/documents/MDOT_RR-102_143535_7.pdf. Accessed:10/21/2014