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

A Tensor Decomposition Approach

By

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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 Denver²

• 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

Subarrays

Mode-1 Fiber $x_{21}$

Mode-2 Fiber $x_{1:2}$

Mode-3 Fiber $X_{1:1}$

Horizontal slice $X_{1::}$

Lateral slice $X_{2::}$

Frontal slice $X_{::3}$
Matricization (Unfolding)

Summation: \( \mathbf{A} + \mathbf{B} = \mathbf{C}, \)
where \( \mathbf{C}_{ijk} = a_{ijk} + b_{ijk} \)

Outer Product: \( \mathbf{X} = \mathbf{a} \circ \mathbf{b} \circ \mathbf{c} \)
s.t. \( x_{ijk} = a_{i} b_{j} c_{k} \)

Khatri-Rao Product: \( \mathbf{P}^{l \times j} \odot \mathbf{Q}^{k \times j} = \mathbf{R}^{l \times k \times j} \)

Kronecker Product: \( \mathbf{P}^{l \times j} \otimes \mathbf{Q}^{k \times l} = \mathbf{R}^{l \times k \times j \times l} \)

Hadamard Product: \( \mathbf{P}^{l \times j} \boxdot \mathbf{Q}^{l \times j} = \mathbf{R}^{l \times j} \)
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

\[ X = \sum_{r=1}^{R} a_r \circ b_r \circ c_r \]

\( a_i, b_i \) 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)

\[ \min_x \| \mathbf{x} - \hat{x} \| \]

Where \( \hat{x} \) is the PARAFAC model

• % Variance Explained

• Core Consistency Diagnostic (CORCONDIAG)
  - High CORCONDIAG \( \rightarrow \) stable model
  - Low CORCONDIAG \( \rightarrow \) 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

<table>
<thead>
<tr>
<th>State</th>
<th>Year</th>
<th>Deck Type</th>
<th>Slab</th>
<th>Stringer/Multibeam Girder</th>
<th>Girder &amp; Floorbeam System</th>
<th>Tee Beam</th>
<th>Box Beam (multiple)</th>
<th>Arch-Deck</th>
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Multidimensional Dataset for analysis
Selected Bridge Design Types

- **Girder and Floorbeam**
- **Slab**
- **Stringer/Multibeam**
- **Arch Deck**
- **Tee Beam**
- **Box Beam**
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%
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


