A Fair Division Approach to Performance-based Cross-Asset Resource Allocation

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Outline

• Background
• Problem
• Concepts
  ▪ Equity, Fair Division approach
• Methodology
• Case Study and Results
• Conclusions
Background

• Allocating resources to finance transportation projects has been a major concern in recent years
• Increasing levels of transportation demand with limited capacity and constrained resources have forced transportation agencies to do more with less
• According to ASCE - $220 billion is needed annually to manage congestion and preserve infrastructure (2010-2040)
Why resource allocation?

- Direct application of TAM principles
- Incorporate multiple conflicting objectives
  - Have challenged decision makers to identify resource allocation strategies that optimize not only an individual asset group but the system as a whole
- Various methodologies have been implemented
  - The methodology, rationale, and analytic support vary significantly in practice
Problem

- Decisions on how to allocate resource across various asset groups involve some trade-off
- Absence of an organized process for cross-asset resource allocation
Problem

- Resource Allocation for single asset class, “silo” approach

“Most transportation funding comes with strings attached and program managers are naturally reluctant to invest in other programs or agencies, given needs typically outstrip available resources”

Source: NCHRP 664: Measuring Transportation Network Performance
Problem

• **Efficiency vs Equity**
  - Optimization schemes provide theoretical solutions, may not be perceived as fair
  - Combination could yield more defensible funding allocation mechanisms
Equity

- Distribution of benefits and whether the distribution is considered appropriate
- Equity in transportation funding allocation
  - With regard to rate of return
  - With regard to performance
  - With regard to need
- Fair Division approach
Fair Division Approach

- New and active are within management science
  - Introduced by Brams and Taylor
- Divide a set of goods $S$ into $N$ shares using a Fair Division scheme
- Various methodologies for divisible, indivisible and mixed goods
Fair Division Approach

- The concept of utility function is typically used to allocating resources fairly among multiple programs

\[
Utility = \frac{Allocated \ Funds}{Needs}
\]

\[
U_i = \frac{F_i}{N_i}
\]

where,

- \( i \) = the \( i \)th player (or program) competing for resource
- \( U_i \) = utility value of the \( i \)th player (or program)
- \( F_i \) = funding received by the \( i \)th player (or program)
- \( N_i \) = resource needed by the \( i \)th player (or program)
Fair Division Approach

• Social Welfare and Collective Utility Functions (CUF)
  ▪ Utility is a measure of the relative satisfaction only, rather than an indication of the fairness of a potential allocation
  ▪ Some of the most important CUFs are utilitarian, egalitarian, elitist, and Nash
  ▪ Example:

<table>
<thead>
<tr>
<th>CUFs</th>
<th>Features</th>
<th>Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilitarian</td>
<td>Objective is to maximize the sum of individual utilities</td>
<td>( SW_{util}(u) = F = \arg \max_F \sum_{i \in I} U_i )</td>
</tr>
</tbody>
</table>
Objective

- Develop a methodological framework for performance-based cross-asset resource allocation using the fair division method, aiming at providing new alternatives for transportation agencies and creating a more defensible resource allocation mechanism.
Methodology

Identify Goals and Objectives

System Condition: Performance Metrics

Allocation Protocol: Fair Division

Trade-off Analysis
Methodology

- Identify Goals and Objectives
  - Transportation agencies need to clearly identify goals and objectives
  - Strategic planning: agency goals, objectives and allocation philosophy
  - Define asset classes
Methodology

• **System Condition**
  - Condition of asset groups.
    - Performance measures.
    - Performance prediction models.
  - Performance-funding relationships.
    - Measure the effects of funding levels on overall condition scores for each asset group.

\[
\text{Performance} = A \cdot (\text{allocated funds})^B
\]
Methodology

- Allocation Protocol
  - Define time horizon
  - Use CUFs (set of rules) to allocate resources
  - Measure allocation fairness:
    - Total utility
    - Total envy
Methodology

- Compute the following parameters for each of the CFUs:

**Total Utility**

\[ \sum_{i=1}^{N} U_i = \frac{F_i}{N_i} \]

**Envy**

\[ \epsilon_{ij} = \begin{cases} |U_i - U_j|, & \text{if } (U_i - U_j) > 0 \\ 0, & \text{otherwise} \end{cases} \]

\[ \sum \epsilon_{ij} = E \]

where,

- \( i \) = the \( i \)th player in the competition for resource;
- \( U_i \) = utility value of the \( i \)th player;
- \( F_i \) = funding received by the \( i \)th player;
- \( N_i \) = resource needed by the \( i \)th player;
- \( \epsilon_{ij} \) = envy experienced by \( i \) from \( j \);
- \( E \) = the total allocation envy.
Methodology

• Allocation Protocol
  - Define time horizon
  - Use CUFs (set of rules) to allocate resources
  - Measure allocation fairness:
    • Total utility
    • Total envy
  - Determine the predicted pavement performance for each asset group
Methodology

• Trade-off analysis

Evaluate various funding alternatives

Fairness: Envy

Optimality: Total Utility & Performance
• **Time horizon:**
  - 3 years

• **Available funds:**
  - 75 percent of total estimated needs

• **Fair Division approach**
  - Envy and utility parameters
### Case Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pavements</th>
<th>Bridges</th>
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<tr>
<td><strong>Condition Measurement</strong></td>
<td></td>
<td></td>
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<tr>
<td>Database</td>
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<tr>
<td>Average CS 2012&lt;sup&gt;1&lt;/sup&gt;</td>
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<tr>
<td>Average SR 2012&lt;sup&gt;2&lt;/sup&gt;</td>
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<td>Estimated Needs ($million)&lt;sup&gt;2,3&lt;/sup&gt;</td>
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<tr>
<td>2013</td>
<td>83</td>
<td>28</td>
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<tr>
<td>2014</td>
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<tr>
<td>2015</td>
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<tr>
<td>2013</td>
<td>A = 46.55; B = 0.15</td>
<td>A = 56.63; B= 0.15</td>
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<tr>
<td>2014</td>
<td>A = 19.81; B = 0.31</td>
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<tr>
<td>2015</td>
<td>A = 19.81; B = 0.31</td>
<td>A = 56.63; B= 0.15</td>
</tr>
</tbody>
</table>

<sup>1</sup> Information from TxDOT Pavement Management Information System (PMIS) database

<sup>2</sup> Information from TxDOT PonTex database

<sup>3</sup> Performance Analysis Tools for Highway Pavement (PATH-P) (Online Source 2014)
### Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Year</th>
<th>Utilitarian</th>
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<td></td>
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<td>Pav</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>2015</td>
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<td>35</td>
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<tr>
<td><strong>Total</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>2014</td>
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<td></td>
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<td>3.000</td>
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<td><strong>Sum</strong></td>
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<tr>
<td><strong>Envy</strong></td>
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**Asset Performance**

- **Pavement Condition Score**
- **Bridge Sufficient Rating**
### Results

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<tr>
<td><strong>Sum</strong></td>
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### Asset Performance

- **Pavement Condition Score**
  - 2012: 95
  - 2013: 90
  - 2014: 85
  - 2015: 80

- **Bridge Sufficient rating**
  - 2012: 95
  - 2013: 90
  - 2014: 85
  - 2015: 80
### Results

<table>
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<th>Parameter</th>
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<td>2.858</td>
<td>0.956</td>
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Conclusions

- Resource allocation across assets as a significant gap
- Methodologies, such as fair division, can serve as a viable alternative to existing allocation methods
- A combination of efficiency and equity have the potential to yield a more defensible funding allocation mechanism
Conclusions

Thank you!

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