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

PMS BMS SMS MMS FMS
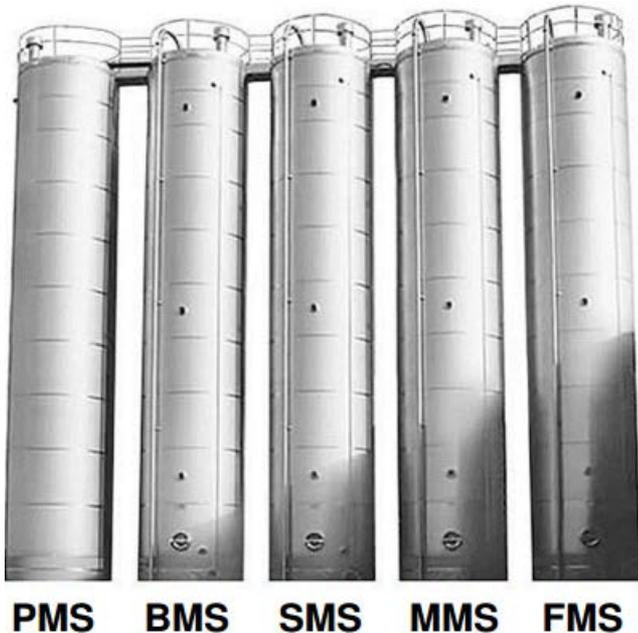
"Most transportation funding comes with strings attached and program managers are naturally reluctant to invest in other programs or agencies, given needs typically outstrip available resources"

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
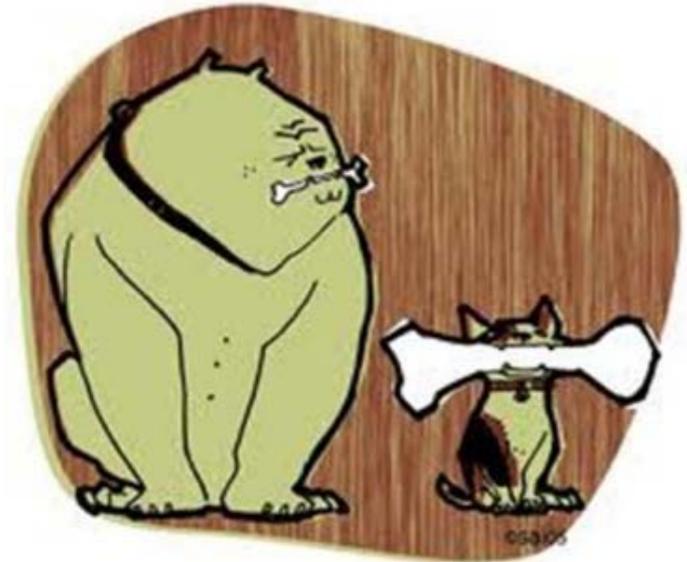
Equity

- 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 ith player (or program) competing for resource

U_i = utility value of the ith player (or program)

F_i = funding received by the ith player (or program)

N_i = resource needed by the ith 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:

CUFs	Features	Formulation
Utilitarian	Objective is to maximize the sum of individual utilities	$SW_{util}(u) = \mathbf{F} = \arg\max_{\mathbf{F}} \sum_{i \in I} U_i$

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
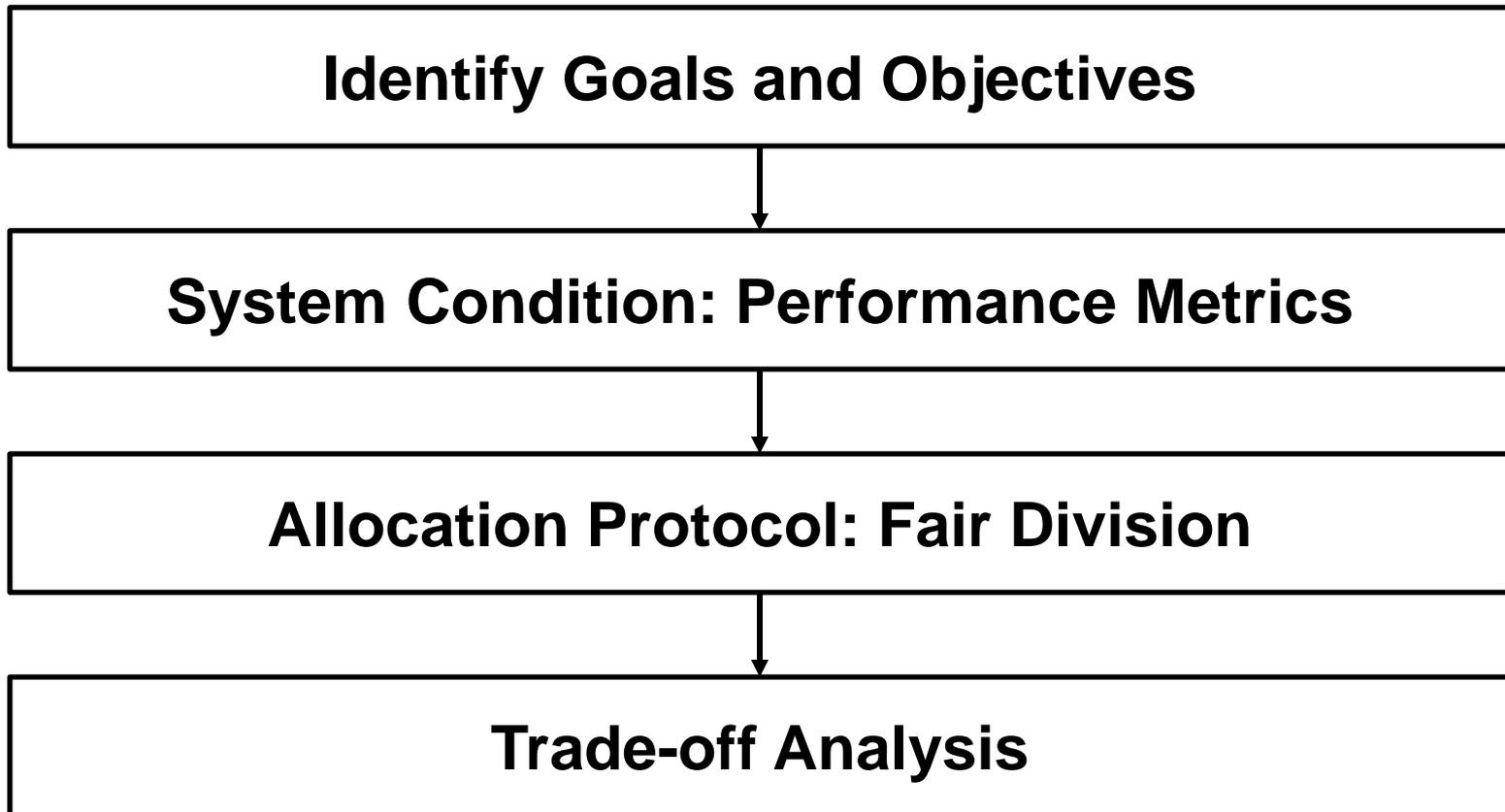
Methodology

- **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

$$\epsilon_{ij} = \left\{ \begin{array}{ll} |U_i - U_j|, & if\left(U_i - U_j\right) > 0 \\ 0\,, & otherwise \end{array} \right\}$$

$$\sum \epsilon_{ij} = E$$

where,

i = the ith player in the competition for resource;
U_i = utility value of the ith player;
F_i = funding received by the ith player;
N_i = resource needed by the ith players;
ϵ_{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
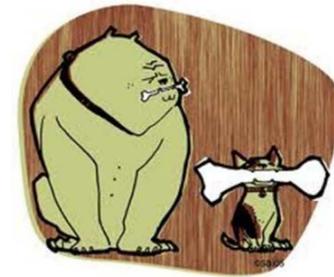
Optimality: Total Utility & Performance

Case Study

Travis County

- **Time horizon**:
  - 3 years

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

- **Fair Division approach**
  - Envy and utility parameters

Case Study

Parameter	Pavements	Bridges
Condition Measurement	Condition Score (CS)	Sufficiency Rating (SR)
Database	PMIS	PonTex
Average CS 2012 [1]	90.14	-
Average SR 2012 [2]	-	90.00
Estimated Needs ($million) [2,3]	-	-
2013	83	28
2014	139	33
2015	139	35
Performance-Funding[4]	-	-
2013	A = 46.55 ; B = 0.15	A = 56.63; B= 0.15
2014	A = 19.81 ; B = 0.31	A = 56.63; B= 0.15
2015	A = 19.81; B = 0.31	A = 56.63; B= 0.15

[1] Information from TxDOT Pavement Management Information System (PMIS) database

[2] Information from TxDOT PonTex database

[3] Performance Analysis Tools for Highway Pavement (PATH-P) (Online Source 2014)

Results

Parameter	Year	Utilitarian	
		Pav	Brid
Allocated Funds ($million)	2013	55	28
	2014	96	33
	2015	96	35
	Total	**247**	**96**
Utility	2013	0.666	1.000
	2014	0.691	1.000
	2015	0.687	1.000
	Total	**2.043**	**3.000**
	Sum	**5.043**	
Envy	2013	0.334	
	2014	0.310	
	2015	0.312	
	Total	**0.956**	

Asset Performance

- Pavement Condition Score
- Bridge Sufficient Rating
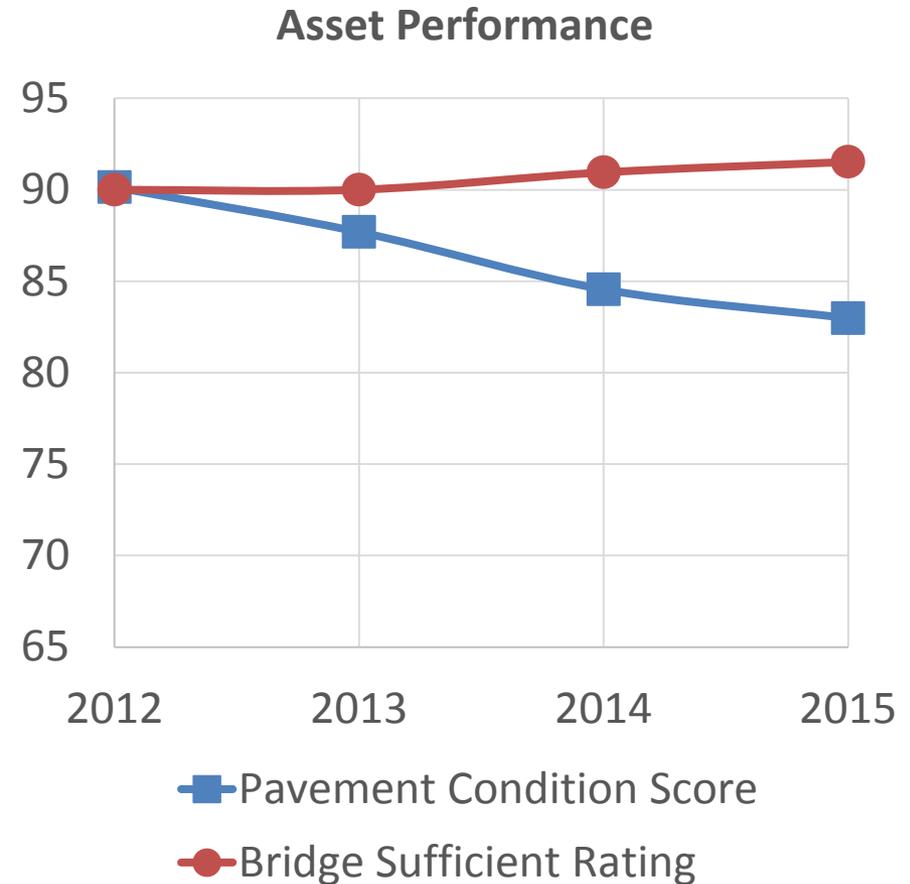
Results

Parameter	Year	Egalitarian	
		Pav	Brid
Allocated Funds ($million)	2013	62	21
	2014	104	25
	2015	104	26
	Total	**271**	**72**
Utility	2013	0.750	0.750
	2014	0.750	0.750
	2015	0.750	0.750
	Total	**2.250**	**2.250**
	Sum	**4.500**	
Envy	2013	0.000	
	2014	0.000	
	2015	0.000	
	Total	**0.000**	

Asset Performance

- Pavement Condition Score
- Bridge Sufficient rating
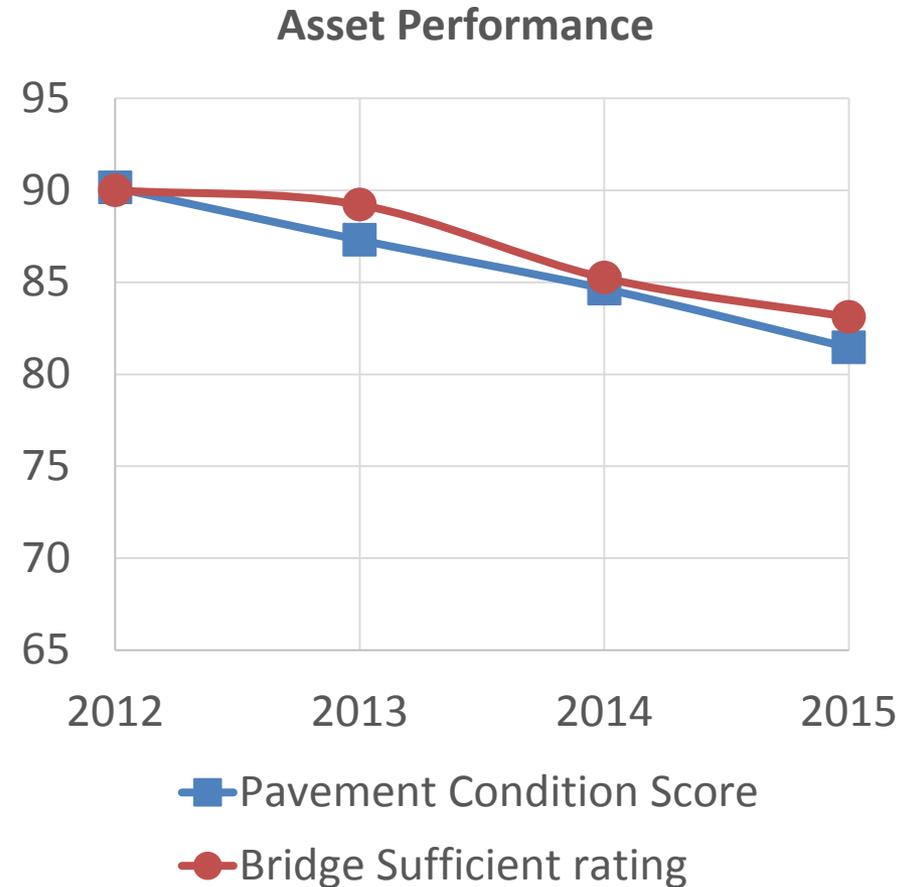
Results

Parameter	Year	Utilitarian		Egalitarian		Elitists		Nash	
		Pav	*Brid*	*Pav*	*Brid*	*Pav*	*Brid*	*Pav*	*Brid*
Allocated Funds ($million)	2013	55	28	62	21	83	0	55	28
	2014	96	33	104	25	129	0	96	33
	2015	96	35	104	26	131	0	96	35
	Total	247	96	271	72	343	0	247	96
Performance	2013	87.69	90.00	85.30	87.78	91.25	78.41	81.91	90.00
	2014	84.55	90.95	81.89	82.51	89.45	62.73	75.69	90.95
	2015	82.98	91.52	76.98	74.26	87.63	56.45	73.21	91.52
Utility	2013	0.666	1.000	0.750	0.750	1.000	0.001	0.666	1.000
	2014	0.691	1.000	0.750	0.750	0.928	0.000	0.691	1.000
	2015	0.687	1.000	0.750	0.750	0.939	0.000	0.687	1.000
	Total	2.043	3.000	2.250	2.250	2.867	0.001	2.043	3.000
	Sum	**5.043**		**4.500**		**2.868**		**5.043**	
Envy	2013	0.334		0.000		0.991		0.334	
	2014	0.310		0.000		0.928		0.310	
	2015	0.312		0.000		0.939		0.312	
	Total	**0.956**		**0.000**		**2.858**		**0.956**	

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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