Managing Transportation Infrastructure Assets in an Era of Limited Resources

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System of Systems

- Energy
- Economy
- Infrastructure
- Social
- Environment
- Political
Example: 2003 Northeast US blackout

- Transportation
  - Fuel
  - Signals
  - Operation
  - Information dissemination
  - More traffic demand generated
- Power
  - Detector failure
  - Mode switch
  - Operational facilities failure
  - Transmitter failure
  - More demand
  - Pump failure
- Telecommunications
  - Fuel
- Gasoline
  - Pump failure
- Water
  - Pump failure
- Sewage
  - Pump failure
- Finance
Transportation Infrastructure Assets

Roads
- Pavements
- Bridges
- Traffic Appurtenances
- Safety Features
- Lighting

Rail & Transit
- Trains/Buses
- Track
- Yards
- Terminals
- Appurtenances

Air Transp.
- Terminals
- Aircraft
- Air Navigation Facilities
- Security Features
- Lighting

Others
- Pedestrian Facilities
- Bike Paths
- Locks & Canals
- Docks/Ports
- Other
## Travel and Goods Movement in Transportation

### U.S. Passenger-Miles (2013)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Passenger-Miles (Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>589,692</td>
</tr>
<tr>
<td>Highway</td>
<td>4,306,717</td>
</tr>
<tr>
<td>Transit</td>
<td>56,467</td>
</tr>
<tr>
<td>Rail</td>
<td>6,804</td>
</tr>
</tbody>
</table>

### U.S. Ton-Miles of Freight (2011)

<table>
<thead>
<tr>
<th>Modes</th>
<th>Ton-Miles of Freight (Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air: domestic</td>
<td>12,134</td>
</tr>
<tr>
<td>Highway: trucks</td>
<td>2,643,567</td>
</tr>
<tr>
<td>Rail</td>
<td>1,725,634</td>
</tr>
<tr>
<td>Water: domestic</td>
<td>499,748</td>
</tr>
<tr>
<td>Oil pipeline</td>
<td>1,018,082</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>86.83%</td>
</tr>
<tr>
<td>Highway</td>
<td>11.89%</td>
</tr>
<tr>
<td>Transit</td>
<td>0.14%</td>
</tr>
<tr>
<td>Rail</td>
<td>0.21%</td>
</tr>
<tr>
<td>Trucks</td>
<td>44.81%</td>
</tr>
<tr>
<td>Domestic water transportation</td>
<td>29.25%</td>
</tr>
<tr>
<td>Pipeline</td>
<td>17.26%</td>
</tr>
</tbody>
</table>
### U.S. Transportation Infrastructure Assets Investment Needs and Shortfall Facts

Cumulative Infrastructure Needs by System Based on Current Trends Extended to 2020 (2010 $ in billions)

<table>
<thead>
<tr>
<th>Category</th>
<th>Total Needs</th>
<th>Estimated Funding</th>
<th>Funding Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Transportation</td>
<td>1,723</td>
<td>877</td>
<td>846</td>
</tr>
<tr>
<td>Airport</td>
<td>134</td>
<td>95</td>
<td>39</td>
</tr>
<tr>
<td>Waterway &amp; Marine Ports</td>
<td>30</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

Data Source: 2013 Report Card for America's Infrastructure, ASCE
U.S. Federal Highway Trust Fund Income

Data Source: FHWA 2013
Vehicle Miles Traveled in U.S. 1988 - 2013

Data Source: FHWA, 2013
# U.S. Highway Pavement Condition

Percent of VMT on National Highway System (NHS) Pavements With Different Levels of Ride Quality

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2005</th>
<th>2007</th>
<th>2009</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI ≤ 95 inches/mile)</td>
<td>50%</td>
<td>52%</td>
<td>57%</td>
<td>57%</td>
<td>60%</td>
</tr>
<tr>
<td>IRI &gt; 170 inches/mile</td>
<td>9%</td>
<td>9%</td>
<td>7%</td>
<td>8%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Good (IRI ≤ 95 inches/mile); Acceptable (IRI ≤ 170 inches/mile) (FHWA, 2012)
## U.S. Highway Bridge Condition - 2013

<table>
<thead>
<tr>
<th>Total Number of Bridges</th>
<th>Number of Deficient Bridges (SD or FO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>607,380</td>
<td>151,238</td>
</tr>
</tbody>
</table>

SD-Structurally Deficient; FO-Functionally Obsolete.

- **Deficient Bridges (SD or FO)**: 25%
- **Not Deficient Bridges**: 75%
Highway Fatalities in U.S. 2002-2012

Number of Fatalities

Persons Fatally Injured in Motor Vehicle Crashes

(FHWA, 2014)
Facility-specific view: Asset Life Cycle

Asset Termination (Demolition, Failure, etc.)
- Assessment of System Vulnerability to disaster,
- Failure Analysis
- Analysis, Description, Optimization and Evaluation of Alternative Demolition Processes

Needs Assessment, Goals Identification, etc.
Does a problem exist?
Assessing the Need for the System
Establishment of System Performance Goals

Asset Preservation
Analysis, Description, Optimization and Evaluation of Alternative Preservation Practices and Maintenance Systems

Asset Planning
Analysis, Description, Optimization and Evaluation of Alternative System Plans, Locations, and Policies

Asset Operations
Analysis, Description, Optimization and Evaluation of Alternative Policy and Operational Systems

Asset Design
Analysis, Description, Optimization and Evaluation of Alternative Designs and Materials

Asset Construction
Analysis, Description, Optimization and Evaluation of Alternative Construction Systems

Source: Sinha and Labi, 2007
Why Asset Management?

- Fiscal Constraints
- Efficient Resource Utilization
- Uncertainty Management
- Accountability
- Sustainability
Reconciling Needs and Funds

FISCAL ANALYSIS

**Funds Needed**
- Asset inventory
- Asset performance modeling
- Performance thresholds (min. LOS)
- Cost analysis of asset treatments
- Effectiveness analysis of asset treatments

**Funds Available (Budget)**

- **REVENUE FORECASTING**
  - Federal/state/local
  - Dedicated funds, specific program areas
  - Matching requirements

- **Other Sources of Revenue**

**PROGRAM DEVELOPMENT**
(What? Where? When?)

- Preservation Projects
- Expansion Projects

**Candidate projects from each program area or mgmt system**
Asset Management Tools

- Inventory of Assets/Conditions and Usages
- Program/ Prioritization/ Optimization
- Trade-off Analyses & Uncertainty Management
- Performance Assessment and Modeling
- Asset Valuation
- Database Development
- Costing and Life-cycle Analysis

Cost-Effective Asset Management
Asset Inventory/ Database

• Inventory size (number of lane-miles, number of bridges, total bridge deck area, etc.)
• Level of usage (volume, loading and condition)
• Role of Technology
Asset Valuation

- Replacement Cost
- Probability of Survival

\[ y_t = e^{-1 \cdot \left( \frac{t}{e^{b_1X_1 + \ldots + b_nX_n}} \right)^\beta} \]

Where, \( \beta \) represents the shape factor, \( b_1 - b_n \) are parameter coefficients; \( X_1 - X_n \) are parameters representing various infrastructure variables

Asset Value at year \( t \) = Replacement Cost at \( t \) \( \cdot \) Probability of survival as of year \( t \)

\[ V_t = (RC) \cdot e^{-1 \cdot \left( \frac{t}{e^{b_1X_1 + \ldots + b_nX_n}} \right)^\beta} \]
Asset Performance: Physical Condition

Poor physical performance

Good physical performance
Asset Performance: Operational

Poor physical performance

Good physical performance

Poor level of service

Good level of service
Why Model Asset Performance?

• Network-level:
  – Forecasting of condition and level of service
  – System-wide work planning
  – Timing of inspection and data collection

• Project-level:
  – Evaluation of the effect of project implementation
  – Life-cycle actions scheduling

• Communication:
  – Both External and Internal
Illustration of Asset Performance Change due to Project Implementation

Performance (IRI)

Pre-treatment Performance Curve

Post-treatment Performance Curve

Performance Jump

Performance at $t$ without rehabilitation project

Performance at $t$ with rehabilitation project

Rehabilitation Project

$T$ (years)
Examples of Performance Indicators: Condition

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Performance Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavements</td>
<td>IRI, RUT, PCR, Deflection</td>
</tr>
<tr>
<td>Bridges</td>
<td>Sufficiency Rating, NBI Rating, Inventory Rating, Geometric Rating, etc.</td>
</tr>
<tr>
<td>Road Signs</td>
<td>Mast structural Condition, Sign Retro-reflectivity, Remaining Service Life</td>
</tr>
</tbody>
</table>

• Note: Some of these are **non-decreasing** PIs (increase with time)

Others are **non-increasing** PIs (decrease with time)
EXAMPLE
Performance Model

- Bridge Deterioration Curve

\[
y = -2E-05x^3 + 0.0027x^2 - 0.1556x + 9
\]

\[R^2 = 0.91843\]
EXAMPLE
Service Life Estimation

\[ y = -2E-05x^3 + 0.0027x^2 - 0.1556x + 9 \]
\[ R^2 = 0.91843 \]
Life-Cycle Cost Analysis

• Activity profile
• Future actions and costs
• Remaining Service Life
Uncertainty Management

Uncertainty Identification
Performance measure variations, construction cost & time overruns, budget uncertainty, extreme events, etc.

Uncertainty Measurement
Probability Distributions, Uncertainty Rating, etc.

Decision-Making under Uncertainty
Probability models, Monte Carlo simulation, expected utility theory, sensitivity analysis, fuzzy set theory, etc.
Integrating Component Systems

- Jurisdictional Database
- Environmental Database
- Traffic Database
- Contract Records Database
- In-house Maintenance Records
- Pavement Management System
- Bridge Management System
- Safety Management System
- Congestion Management System
- Highway Drainage Management System
Project Selection/ Programming

Program Candidate Pool

- Pavement Projects
- Bridge Projects
- Safety Projects
- Congestion Projects
- Other Projects

Optimal Decision-making Based on Multiple Performance Measures/Objectives

SELECTING THE BEST PROJECT PORTFOLIO FOR IMPLEMENTATION

- Asset Management Objectives
- Budget Constraints
- Performance Thresholds
Program Analysis

– constraints to the overall AM Budget
– constraints to budgets of individual program areas
– constraints to performance thresholds in each program area or management system
– political constraints
Trade-off Analysis: Pareto Solutions and Pareto Frontier

Minimize both $f_1(x)$ and $f_2(x)$
Trade-off between Cost and Performance Measures

Examples

Network-Level Average IRI (inches/mile)

\[ y = 4E-08x^4 - 3E-05x^3 + 0.0093x^2 - 1.5759x + 179.05 \]

\[ R^2 = 0.99909 \]

Network-Level Average RSL of Safety Assets (Years)

\[ y = -8E-07x^6 + 6E-05x^5 - 0.0021x^4 + 0.0356x^3 - 0.3283x^2 + 1.7083x + 4.7861 \]

\[ R^2 = 0.99794 \]

Percent of BCR ≥ 5

\[ y = 1E-06x^5 - 0.0001x^4 + 0.0071x^3 - 0.1969x^2 + 3.8896x + 52.483 \]

\[ R^2 = 0.99875 \]

Note:
IRI—International Roughness Index
BCR—Bridge Condition Rating
RSL—Remaining Service Life
Trade-offs between two performance measures

E.g., How much safety performance can be traded off for a given level of mobility performance?

Specifically, by shifting $X$ from congestion to safety budget, how many crashes could AM reduce for each 1% reduction in v/c ratio?
Two-dimensional trade-off analyses under different budget levels

\[ y = -0.0000925x^4 + 0.0417011x^3 - 7.06158x^2 + 532.717x - 15,019.3 \]

\[ R^2 = 0.998 \]
Shifting budget between subareas with a fixed total budget ($80M)

<table>
<thead>
<tr>
<th>Pavement Budget ($M)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bridge Budget ($M)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Average IRI (inches/mile)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
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<tr>
<td>Pavement Budget ($M)</td>
<td>70</td>
<td>60</td>
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<td>40</td>
</tr>
<tr>
<td>Bridge Budget ($M)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Average IRI</td>
<td>94.24</td>
<td>100.54</td>
<td>108.28</td>
<td>114.56%</td>
</tr>
<tr>
<td>Percent of BCR&gt;=5</td>
<td>74.65%</td>
<td>88.73%</td>
<td>94.67%</td>
<td>97.33%</td>
</tr>
</tbody>
</table>
**Trade-off analysis - Price of Confidence**

To reach the same performance level, under different confidence levels, the costs are different.

By investigating the cost at different confidence levels, the price of the confidence can be evaluated.
Future Directions
System of Systems

- Interaction with Higher Level Systems
- Infrastructure Impact on Economy
- Role of Alternative Energy Sources

Pricing/Financing

- Internalization of Hidden Costs
- VMT Fees
- Increased Use of PPP
Climate Change

• Sea Level Rise
• High Temperatures and Heat Waves
• Increases in Intense Precipitation
• Increases in Hurricane Intensity
• Others

- Hurricanes
- Increased frequency of freeze–thaw cycles
- Flooding
Climate Change Adaptation

• Which climate change impacts are most relevant in a given area?
• How will climate change affect transportation system?
• What are the interdependencies among asset types?
• How should transportation decision makers respond?
• What data and decision support tools are needed?
• Which adaptation strategies make sense?
Risk & Uncertainty

• Performance/ Budget/ Revenue/ Cost
• Natural Disasters (Earthquake/ Flooding)
• Man-made Events
• Asset & Network Vulnerability/Resilience Evaluation
Asset Management & Sustainability

- Appropriate pricing
- Access management, facilities for walking, bicycling, and transit
- Incentives for green construction
- Recycling
- Low emission materials, etc.

Scheme of Sustainable Development

Economic Vitality

Viable

Equitable

Bearable

Sustainable

Environmental Management

Quality of Life/Social Justice
Increased Use of Technology

• ITS / AV / V2V / V2I
• Automated User Fee Collection
• Remote Distress Monitoring
• Automated Condition Data Collection

Role of Social Media

• System Planning
• Real Time Traffic Control
• Network Resilience
Take Aways

- System of Systems
- Pricing
- Political Climate
- Optimization
- Tradeoffs
- Technology
- Risk and Uncertainty
- Sustainability/Climate Change
- Network Resilience
- Role of Social Media