A Multi-Criteria Methodology for Measuring the Resilience of Transportation Assets and Prioritizing Security Investments

Flood damage at the bridge over Blackburn Fork along Pippin Road in northern Putnam County, Tennessee. Taken by: Brian Stansberry

Michelle Dojutrek, Samuel Labi, J. Eric Dietz
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Outline

- Motivation
- Problem Statement
- Objectives
- Literature Review
- Terminology
- Methodology
- Case Study
- Prioritization

Motivation (1 of 5)

■ Unintended Termination of Infrastructure

■ Internal Cause

- Design flaw
- Fatigue failure
- Advanced deterioration
- Other internal cause

■ External Cause

- Overloading
- Accidents
- Natural Events
- Other external causes

2006 Complete Bridge Failure I-35 Minnesota Bridge
due to faulty gusset plate

2013 Philippines Typhoon

Motivation (2 of 5)

Hurricane Katrina (\$108B)

Japan Tsunami
(\$309B)

Hurricane Sandy
(\$50B)

Motivation (3 of 5)

- Key Steps in Infrastructure Risk Management
 - Measure the threat likelihood posed by external or internal threats to the asset
 - Monitor the threat likelihood over time
 - Assess the effectiveness of actions intended to reduce consequences
 - Communicate this information to general public and legislators
 - Provide evidence for appropriate resources
 - To complete the above, a method to quantify security is needed

Motivation (4 of 5)

- Including security as a performance measure in transportation project evaluation
 - There exist a number of assets in *high threat area*
 - Current funding allocation process focuses on:
 - Asset performance measures
 - Asset age
 - Maintenance cycle
 - Budget
 - How to consider assets in high security area?
 - Need a method to quantify security

Motivation (5 of 5)

- Uncertainty of Security Factors
 - Hazards are highly non-deterministic
 - Magnitude of Earthquakes
 - Number of Accidents
 - Asset Failure
 - Failure to consider uncertainty will lead to:
 - Assets being unprepared for potential hazards
 - Greater consequences
 - Can be predicted probabilistically based on:
 - Historical data trends
 - Predictive Models

Problem Statement

- **Problem:** How to quantify security based on relevant security factors
 - Prioritize assets in terms of security for investment purposes
 - Incorporate security into investment evaluation

Objectives

- Develop a methodology to quantify security
 - Measure the threat likelihood of threats to the asset
 - Monitor the threat likelihood over time
 - Assess the effectiveness of actions intended to reduce consequences
 - Communicate this information to general public and legislators
 - Provide evidence for appropriate resources
- Apply methodology to carry out prioritization of security investments
- Apply methodology to investment evaluation on the basis of multi-criteria

Literature Review

- Risk Assessment Key Elements
 - What could go wrong?
 - What is the likelihood that it will go wrong?
 - What are the consequences if it goes wrong?

(Ezell et al. 2000)

Literature Review

■ AASHTO Vulnerability Assessment

Vulnerability:

- Visibility & Attendance
- Access to Asset
- Site Specific Hazards

Criticality:

- Deter/Defend Factors
- Loss & Damage Consequences
- Consequences to Public Services
- Consequences to General Public

Literature Review

■ CARVER+Shock

- Criticality
- Accessibility
- Recuperability
- Vulnerability
- Effect
- Recognizability
- Shock

Incorporates the combined health, economic, and psychological impacts of an attack on the target system

1. Factors are subjectively assigned a value on a scale of 0-10

2. The overall vulnerability score of a single target is the sum of the scores assigned to the several criteria

3. Score can be compared to rank the vulnerability of the different targets relative to each other

Literature Review

■ Costing Asset Protection for Transportation Agencies (CAPTA)

- *Consequence-driven* approach
- Set consequence thresholds for:
 - Potentially exposed population
 - Property loss
 - Mission disruption

Used as a capital budgeting prioritization tool,
not asset-specific assessment tool

Inputs:

- Consequence thresholds
- Threats of concern
- Asset class

Outputs:

- Mitigating countermeasure for specific asset/hazard combination
- Prioritized asset & countermeasure within budget

Gaps in Literature

- Different definitions
 - Vulnerability & Criticality similarities
 - Criticality includes consequences (AASHTO)
 - Vulnerability and Criticality separate
- Considered in inappropriate way
 - Criticality vs. vulnerability vs. hazard likelihood
- Current risk equation missing key inputs
 - Risk= (consequence x vulnerability x threat)
 - Resilience?

Terminology

	Term	Definition	Consistent with:
Assets	<i>Target</i>	Transportation asset that has value to the owner or users	(SAIC & PB Consult, 2009)
	<i>Resilience</i>	The ability of the asset to withstand the threat	(Flynn and Burke, 2011)
Threats	<i>Threat</i>	An unexpected natural, unintentional man-made or intentional man-made event that causes damage or disruption	(SAIC & PB Consult, 2009)
	<i>Threat Likelihood</i>	The probability of a threat effecting the asset	(Ayyub et al., 2007)
Consequences	<i>Consequence</i>	The loss of an asset and its associated costs and damages	(SAIC & PB Consult, 2009)

Methodology

■ Framework

■ Input Factors:

- Threat Likelihood
- Resilience
- Consequences

■ Output:

- Security Rating
- Prioritized Assets
- Multi-criteria Evaluation

Methodology

Methodology

Factor	$F_i = w_1 M_1 + \dots + w_j M_j$ <p>Where F_i is security factor i, w_j is weight of measure j, and M_j is security measure j</p>										
Measure	$M_j = \frac{s_1 \times \dots \times s_N}{N}$ <p>Where s_N is security attribute of measure j, N is the total number of security attributes for measure j of factor i</p>										
Attribute	$s_N \rightarrow \text{scaled}$ <table border="1"> <tr><td>1</td><td>Good</td></tr> <tr><td>2</td><td></td></tr> <tr><td>3</td><td></td></tr> <tr><td>4</td><td></td></tr> <tr><td>5</td><td>Bad</td></tr> </table>	1	Good	2		3		4		5	Bad
1	Good										
2											
3											
4											
5	Bad										
Security Rating	$\text{Security Rating} = \frac{\sum \text{factors that improve security}}{\sum \text{factors that decrease security}}$										

Methodology

- Factor 1: Likelihood of Threat
 - Degree of susceptibility of an asset to a specific threat [hazard]

Measures:	Attributes:
Location Specific Hazards	Natural Hazards Freeze Index Precipitation
Access to Asset	Environmental Barriers Physical Barriers

Methodology

- Factor 2: Resilience
 - Ability of asset to maintain essential functions with little disruption or when disrupted will recover functions rapidly

Measures:	Attributes:
Resistance	Condition Age
Recoverability	Construction Time Construction Cost Asset Size
Asset Characteristics	Material Design Type

Methodology

- Factor: Consequence
 - Outcome of hazard or threat on an asset

Measures:	Attributes:
Potentially Exposed Population	Population ADT
Property Loss	Replacement Cost Value
Mission Disruption	Detour Length Travel Time Increase

Methodology

■ Security Rating

- Measure of degree of asset security in regard to specific threats
 - Resilience/(Threat Likelihood + Consequences)
 - Weights (expert opinion, literature)
 - Greater SR = more secure asset

$$SR_a = \frac{F_{R_a}^{\alpha}}{\left(F_{TL_a}^{\delta} + F_{C_a}^{\lambda}\right)}$$

Where SR_a is the Security Rating for asset a ; F_{TL_a} is the threat likelihood factor of asset a ; α is the exponential weight of the resilience factor; F_{C_a} is the consequence factor of asset a ; δ is the exponential weight of the threat likelihood factor; F_{R_a} is the resilience factor of asset a ; and λ is the exponential weight of the consequence factor.

Methodology

- Security Rating Factors
 - Threat Likelihood vs. Resilience

Methodology

- Security Rating Factors
 - Consequence vs. Resilience

Methodology

- Security Rating Factors
 - Threat Likelihood vs. Consequence

Methodology

- Security Rating Factors
 - 3 Dimensions

Interpretation of Security Rating

Security Rating	Example Interpretation
≤ 0.21607	Indicates very high security improvement needs and low resilience thus immediate action should be undertaken to enhance resilience and thus reduce the possible consequences.
$0.25446 - 0.21608$	Indicates high security improvement needs of the asset. The agency should be ready to undertake actions to enhance resilience and thus to reduce the possible consequences of the asset failing.
$0.39976 - 0.25447$	Indicates medium-to-high security improvement needs. Facilities within this range can be monitored at a frequency slightly exceeding standard frequency. The risk of failure can be tolerated until a normal capital project (to enhance resilience and thus reduce consequences, among other benefits) is carried out.
$0.94981 - 0.39977$	Indicates low-to-medium security improvement needs. Unexpected failure can be avoided during the remaining service life of the asset by performing standard scheduled inspections with due attention to specific design features that influence the assets possible consequences.
$3.03203 - 0.94982$	Indicates low security improvement need. Often reflective of the likelihood of threat to a civil engineering system built to the current design standards in a low threat likelihood environment.
$11 - 3.03204$	Indicates little or no security improvement needs.

Project Level Case Study

- Bridge # 8868 JFK Bridge
 - Jeffersonville, IN
 - Clark County

Assumptions

- Construction time based on asset size
- Probability of earthquake threat based on amount of historical earthquake epicenters in county
- Environmental barriers = if over waterway
- Physical barriers = if roadway under bridge
- Detour travel speed 45mph
- Assume α , δ , λ are equal weights

Project Level Case Study

■ Factor 1: Threat Likelihood

Measure	Attributes	Data	Scaled	Equation
Access to Asset	Env Barriers	Over river	3	$M_{access} = \frac{S_{environmental} \cdot S_{physical}}{N_{attributes}}$ <p>4.5</p>
	Physical Barriers	Roadway underneath	3	
Location Specific Hazards	Natural Hazards	Earthquake epicenter	1	$M_{location} = \frac{S_{natural} \cdot S_{freeze} \cdot S_{precipitation}}{N_{attributes}}$ <p>1.67</p>
	County Freeze Index	30	1	
	County Precipitation	45.84	5	

$$F_{TL} = w_{access} \cdot M_{access} + w_{location} \cdot M_{location}$$

$$F_{TL} = 0.5 \cdot 3 + 0.5 \cdot 2.33$$

2.67

Project Level Case Study

■ Factor 2: Resilience

Measure	Attributes	Data	Scaled	Equation
Resistance	Condition	Deck: 6	2	$M_{resistance} = \frac{S_{condition_i} \cdot S_{age}}{N_{attributes}}$ $i = 1 \dots I$ 12
		Superstructure: 5	3	
		Substructure: 6	2	
	Age	83 yrs	4	
Recoverability	Const. Time	2yrs	4	$M_{recoverability} = \frac{S_{time} \cdot S_{size}}{N_{attributes}}$ 41.67
	Const. Cost	\$45.2M	5	
	Asset Size	267,466 ft ²	5	
Asset Characteristics	Material	Continuous steel	3	$M_{characteristics} = \frac{S_{material} \cdot S_{design}}{N_{attributes}}$ 3.5
	Design Type	Truss Bridge	4	

$$F_R = w_{resistance} \cdot M_{resistance} + w_{recoverability} \cdot M_{recoverability} + w_{characteristics} \cdot M_{characteristics}$$

$$F_R = 0.33 \cdot 12 + 0.33 \cdot 41.67 + 0.33 \cdot 3.5$$

19.2

Project Level Case Study

■ Factor 3: Consequences

Measure	Attributes	Data	Scaled	Equation
Potentially Exposed Population	Population	Jeffersonville: 27,362 Clark County: 96,472	3	$M_{population} = \frac{S_{population} \cdot S_{AADT}}{N_{attributes}}$ <p style="text-align: center; color: red;">3</p>
	AADT	15,200	2	
Property Loss	Replacement Cost	\$36.1M	4	$M_{property} = \frac{S_{rcost} \cdot S_{value}}{N_{attributes}}$ <p style="text-align: center; color: red;">8</p>
	EDMC Value	\$18.63M	4	
Mission Disruption	Detour Length (miles)	3.11	2	$M_{disruption} = \frac{S_{detour} \cdot S_{tt}}{N_{attributes}}$ <p style="text-align: center; color: red;">2</p>
	Inc in travel time due to detour	4.15 min	2	

$$F_C = w_{population} \cdot M_{population} + w_{property} \cdot M_{property} + w_{disruption} \cdot M_{disruption}$$

$$F_C = 0.33 \cdot 3 + 0.33 \cdot 8 + 0.33 \cdot 2$$

4.29

Project Level Case Study

■ Factor Security Ratings

■ F_{TL} , F_R , F_C

+ Average of all Bridges in Indiana

■ High Importance ■ Med Importance ■ Low Importance

Project Level Case Study

- Security Rating
 - JFK Bridge

SRnew

●	0.07077 - 0.21607
●	0.21608 - 0.25446
●	0.25447 - 0.39976
●	0.39977 - 0.94981
●	0.94982 - 3.03203
●	3.03204 - 10.91429

$$SR_a = \frac{F_{R_a}^{\alpha}}{\left(F_{TL_a}^{\delta} + F_{C_a}^{\lambda}\right)}$$

$$SR_{JFK} = \frac{19.2^1}{\left(2.67^1 + 4.29^1\right)} = 2.76$$

Multi-Criteria Evaluation and Security Rating

Multi-Criteria Evaluation

- Incorporating Security Rating into Evaluation
 - Multiple-Criteria Evaluation: Include, as one of the multiple performance measures (PM):

- **"Security Rating"**

or/and

- **"Increase in Security Rating"**

or/and

- **"Final Security Rating"**

Generic PM (is the same for each project alternative)

Alternative-specific PM (is different for each project alternative)

Alternative-specific PM (is different for each project alternative)

Multi-Criteria Evaluation

- Existing Security Rating (Simple Preliminary Illustration)
 - Considers an asset's security rating before any work is performed

Asset	Existing Security Rating (ESR)	Priority Rank on the Basis of Existing Security Rating
Asset 1	3.22	2
Asset 2	2.45	1
Asset 3	5.65	3
Asset 4	7.40	5
Asset 5	10.23	6
Asset 6	6.89	4

High security ratings = more secure asset ∴ low security rating = higher importance for investment

Multi-Criteria Evaluation

- Increase in Security Rating (Simple Preliminary Illustration)
 - Considers the increase in security rating due to an improvement to an asset (SR after improvement minus existing SR)

Asset	Improvement	ESR ¹	ISR ¹ (ΔSR)	Rank of ESR	Rank of ISR
Asset 1	Bridge Deck Overlay	3.22	4.57	2	4
Asset 2	Bridge Substructure Maintenance	2.45	8.30	1	1
Asset 3	Bridge Rehabilitation	5.65	7.22	3	2
Asset 4	Bridge Painting	7.40	0.52	5	6
Asset 5	Added Travel Lane on Bridge	10.23	1.32	6	5
Asset 6	Bridge Superstructure Replacement	6.89	4.88	4	3

¹ESR: Existing Security Rating; ISR: Increase in Security Rating

High increase in security ratings = greater increase in security of asset

Multi-Criteria Evaluation

- Final Security Rating (Simple Preliminary Illustration)
 - Considers the asset's security rating after an improvement is performed on the asset

Asset	Improvement	ESR	ISR (Δ SR)	FSR (SR + Δ SR)	Rank of ESR	Rank of ISR	Rank of FSR
Asset 1	Bridge Deck Overlay	3.22	4.57	7.79	2	4	6
Asset 2	Bridge Substructure Maintenance	2.45	8.30	10.75	1	1	4
Asset 3	Bridge Rehabilitation	5.65	7.22	12.87	3	2	1
Asset 4	Bridge Painting	7.40	0.52	7.92	5	6	5
Asset 5	Added Travel Lane on Bridge	10.23	1.32	11.55	6	5	3
Asset 6	Bridge Superstructure Replacement	6.89	4.88	11.77	4	3	2

¹ESR: Existing Security Rating, ISR: Increase in Security Rating, FSR: Final Security Rating

High security ratings = more secure asset

Multi-Criteria Evaluation

■ Evaluation Performance Measures

■ Example Criteria

- Air quality
- Noise
- Economic efficiency
- Economic development
- Travel time
- Safety
- VOC
- Connectivity

■ Add Security Rating

Add benefits of enhanced security to overall benefits

Add costs associated with enhancing security to overall costs

$$\frac{\sum B_i}{\sum C_i}$$

Where, i is criteria 1...I

Questions?