Integration of Resilience and Risk to Natural Hazards into Transportation Asset Management of Road Networks: A Systematic Review

14th Aug 2023

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Content

- Paper Review Methodology
- Integration Requirements
- Risk and Resilience Modeling
- Integration Methods
- Limitations in state of Art and Practice

Publication process

Integration of Resilience and Risk to Natural Hazards into Transportation Asset Management of Road Networks: A Systematic Review

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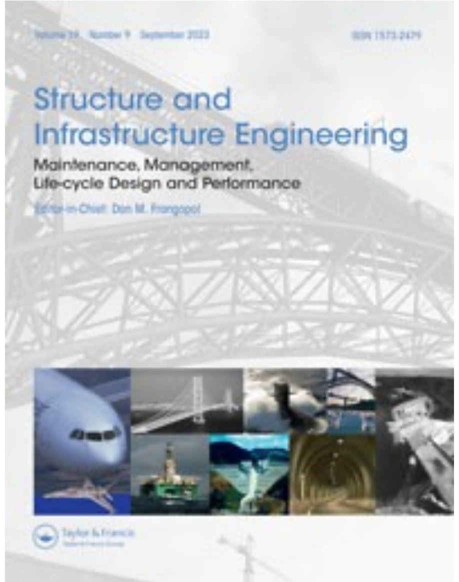

Current State: Accepted, editing process
DOI: 10.1080/15732479.2023.2238281

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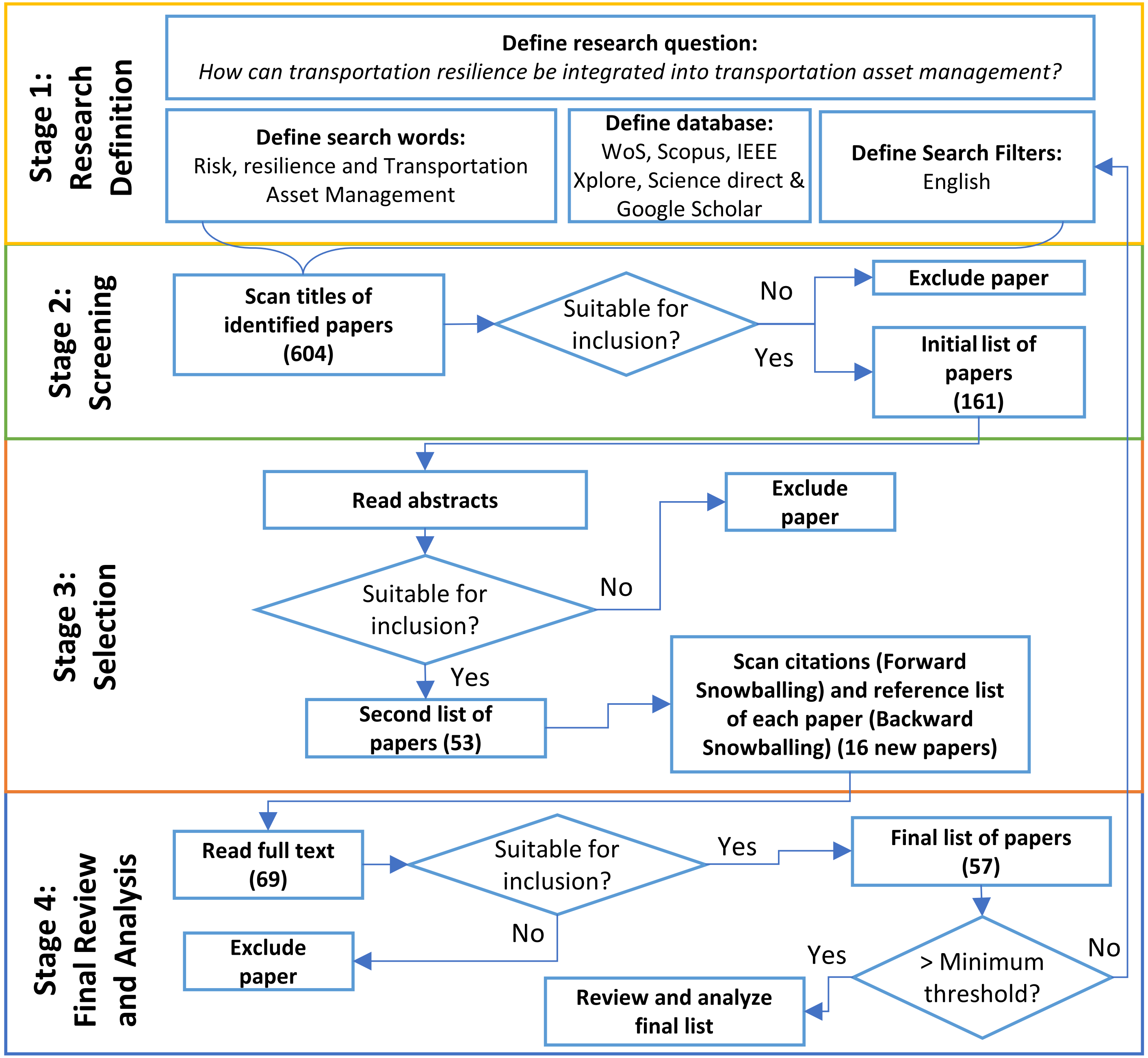
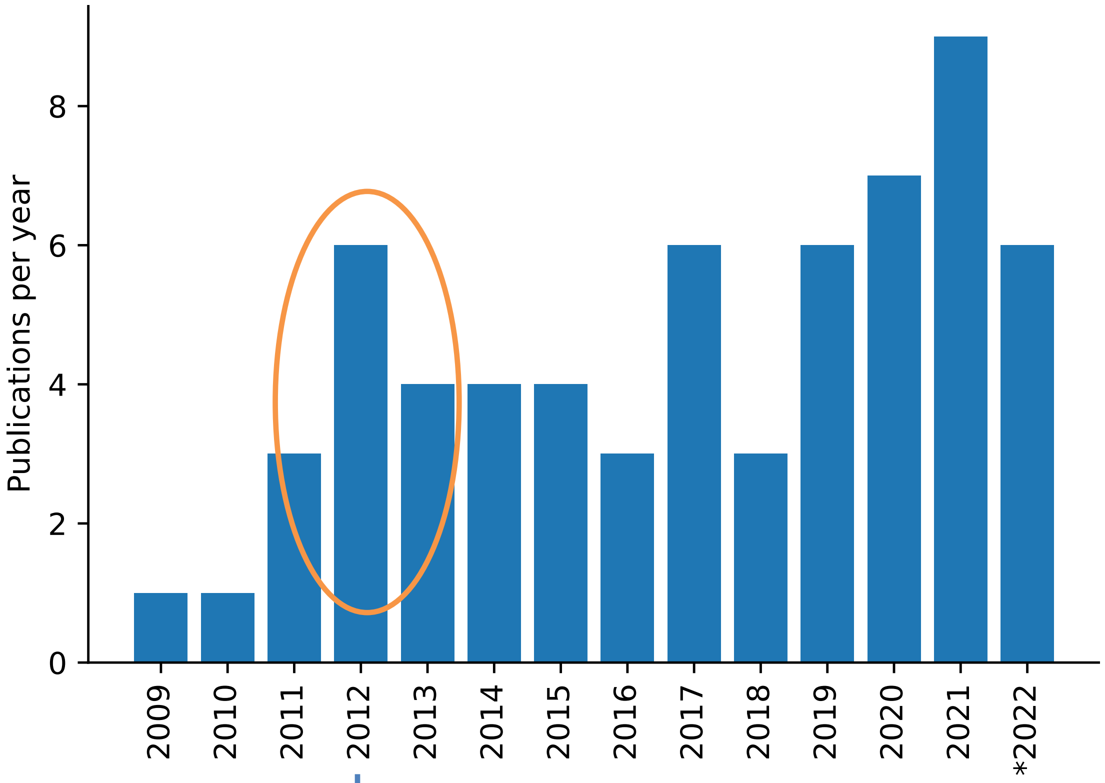


Review Methodology

Allen et al., 2023

Some Statistical Analyses

Publication Distribution per Year

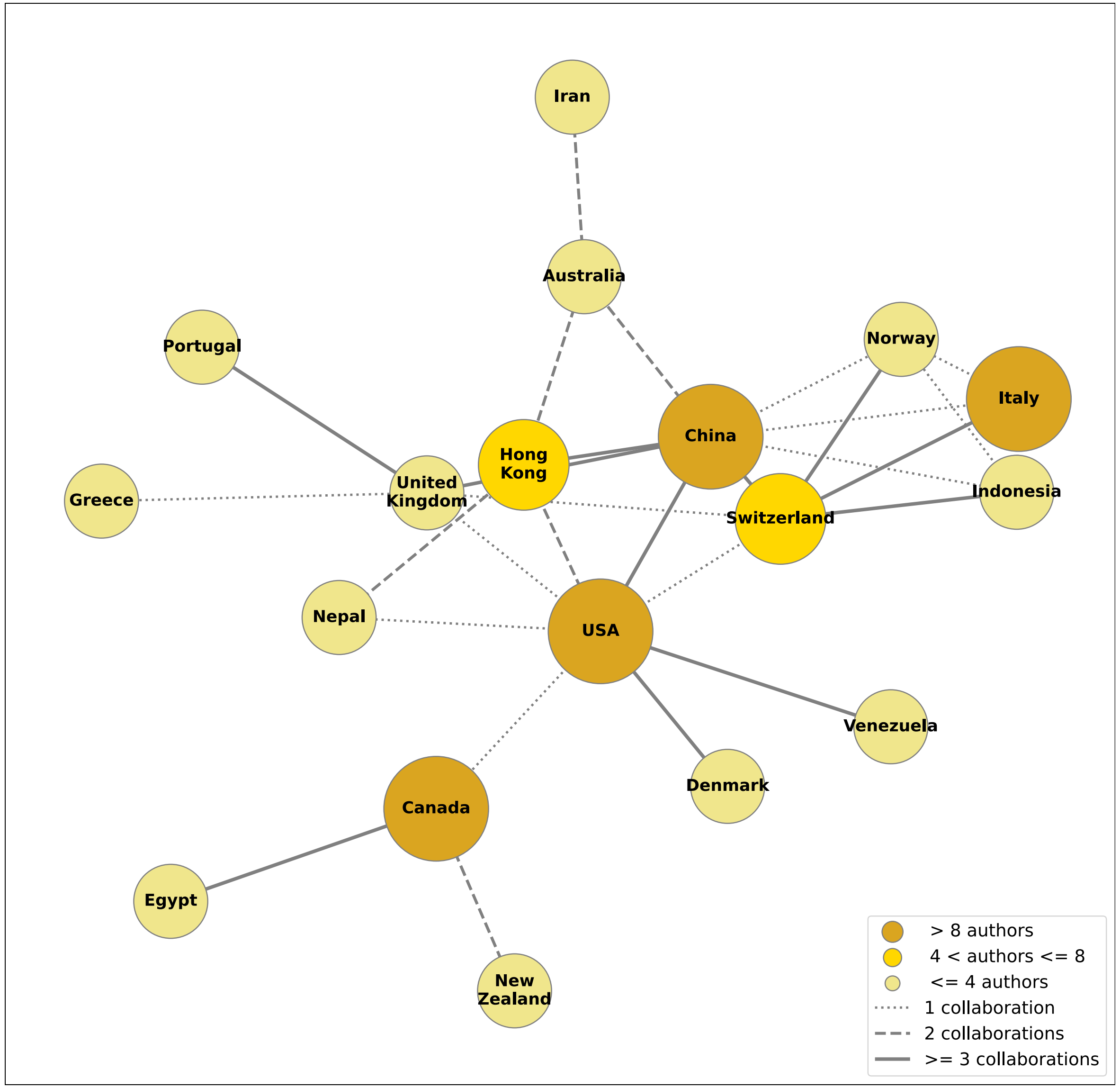


Year of Publication
*: Until June

Allen et al., 2023

In 2012 and 2013, FHWA published a series of reports entitled "**Risk-based transportation asset management**"

International collaborations



How to integrate risk and resilience into transportation asset management?

Integration requirements and policy guidelines

Risk and Resilience modeling for integrated Transportation Asset Management

Integration Methods

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Integration requirements and policy guidelines

The Need for Integration

Moving ahead for progress in 21st century (**MAP-21**) requires states **to develop a risk-based asset management** (NHS) to improve or preserve the condition of the assets and the performance of the system (Liu and McNeil, 2020)

The guidance document from the **English Highway Agency** explains the importance of risk management, explains roles and responsibilities and provides policies of risk management (Saadatmand, Gaj and Proctor, 2012)

In New Zealand, transportation agencies are **mandated by law** to implement and report on risks and management of risk to assets (Varma and Proctor, 2012)

The Australia Transport agency has introduced and implemented the ISO 31000 framework as part of its asset management program (Way, 2010)

Transport **Scotland** (TS)'s Road Asset Management Plan (RAMP) includes a chapter on risk management, illustrating the common use of risk management (Saadatmand, Gaj and Proctor, 2012)

Policy Guidelines/Manuals

Policy Guidelines/Manuals

Recommendations

- Develop a **risk assessment** of state's transportation infrastructure
- **Strengthen** existing transportation networks
- **Define risk management leadership** (Curtis et al, 2012)
- Strategically expand transportation networks in order to **create redundancies** (Curtis et al, 2012)
- A disaster data revolution is needed that involves systematic collection on disaster risk (Henning et al., 2017)

Benefits

- Mitigate the risks asset may present to the management of transportation networks
- Identifying most fragile assets (Yang et al., 2019)
- Assessment of the greatest hazards based on a probability and impact assessment (Saadatmand et al., 2012)
- Avoid "managing by crisis" and promotes proactive management strategies (Proctor et al., 2013)

Policy Guidelines/Manuals

Table 1: Overview guidelines and standards

Title	Country of origin	Framework	Hazard analysis	Resilience & risk assessment	Recommendations
Risk-Based Transportation Asset Management (Saadatmand et al., 2012b; Varma & Proctor, 2012; Saadatmand et al., 2012a, 2013; Proctor et al., 2013)	United States	•		•	•
ISO 31000 (International Organization for Standardization, 2018)	International (ISO)	•			•
Risk Management Process Manual (Transit New Zealand, 2004)	New Zealand	•	•	•	
Road Transport Management Framework and Principles (Karndacharuk et al., 2017)	Australia	•		•	
Transport Scotland Road Asset Management Plan (Transport Scotland, 2016)	Scotland	•			•
A Risk-based framework for asset management (Highways Agency, 2010)	England	•	•	•	•
Integrating Climate Change into Road Asset Management (Henning et al., 2017)	International (World Bank)	•			•

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Risk and Resilience modeling for integrated Transportation Asset Management

Risk Modeling

Deterministic Approach

Risk Priority Number

Strategic importance of each asset

$$RPN = Occurrence\ x\ seveverity\ x\ Strategy$$

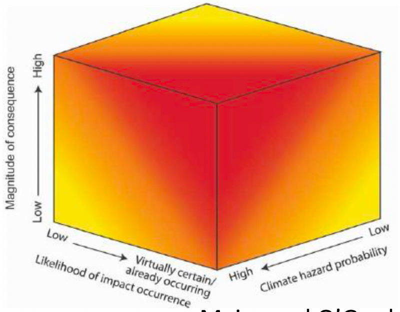
Chang et al, 2020

$Occurence =$ Probability of an asset experiencing at least one extreme climate event during its service life

$Severity =$ Probability of an asset experiencing failure or damage at the time of occurrence of the extreme climate event

		Consequence level			
		Minor	Moderate	Major	Catastrophic
Probability level		**1**	**2**	**3**	**4**
Low	**1**	1	2	3	4
Medium	**2**	2	4	6	8
High	**3**	3	6	9	12
Very high	**4**	4	8	12	16

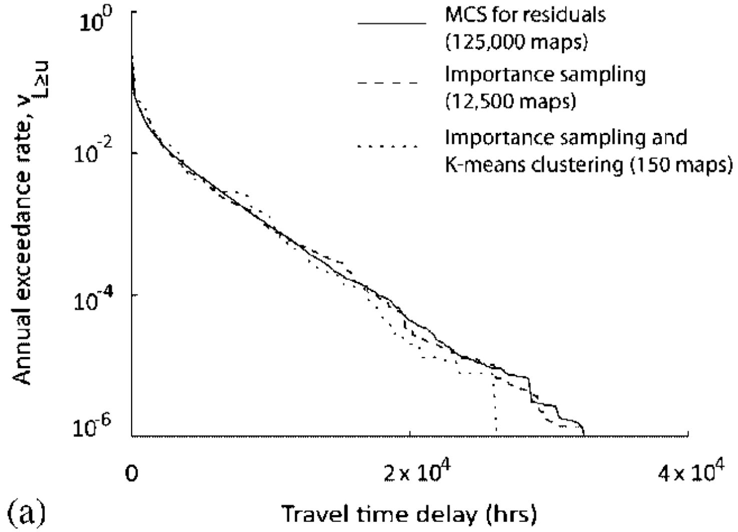
Alberti and Fiori, 2019



Major and O'Grady, 2010

Risk matrices consider the consequences to the infrastructure and the probability level (associated to the Hazard likelihood)

Probabilistic Approach



Jayaram and Baker, 2010

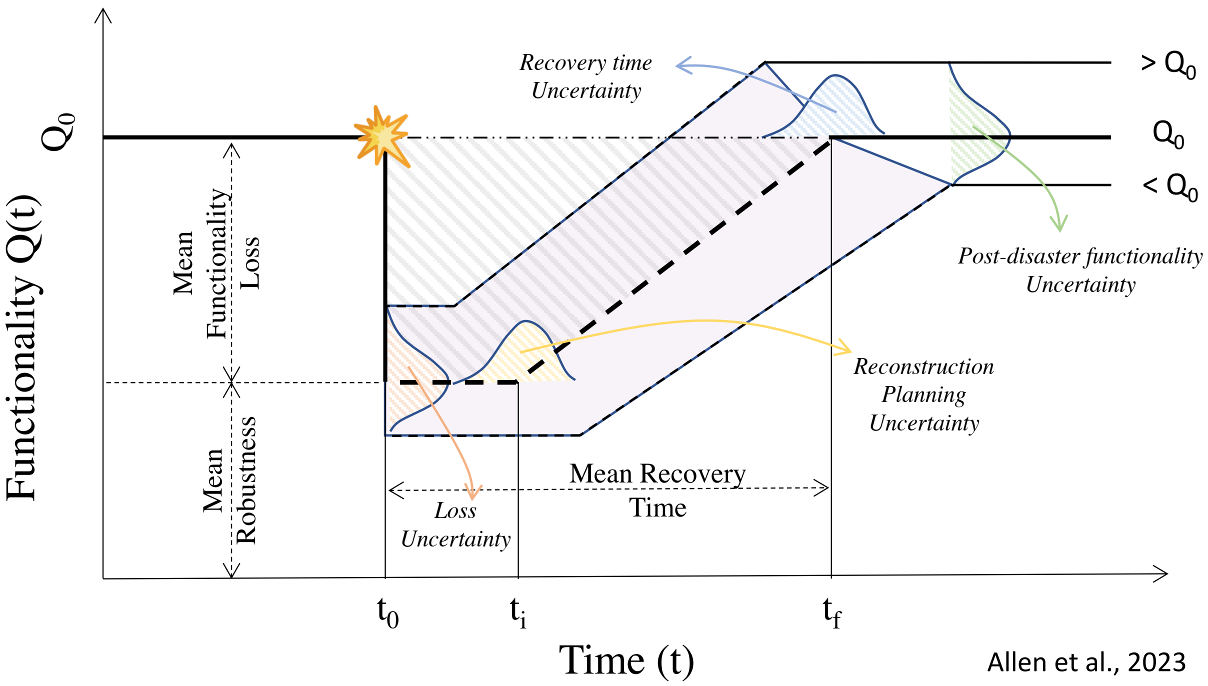
Spatially Distributed Network Risk Assessment

$$\lambda_{DV}(dv) = \nu \int_{\Omega \in R^n} \underbrace{P(DV > dv | \overline{\boldsymbol{IM}} = \overline{\boldsymbol{im}})}_{\text{Fragility}} \underbrace{f_{\overline{IM}}(\overline{\boldsymbol{im}}) d\overline{\boldsymbol{im}}}_{\text{Hazard}}$$

dv: Decision Variable
IM: Intensity Measure
v : Hazard annual rate (selected set of events)
λ_{DV} : Annual rate of exceedance of decision variable **dv**

How to define and calculate resilience?

Performance-based Approach



Allen et al., 2023

These metrics consider the effect of natural hazards on infrastructure over time and allow decision makers to use a variety of different performance indicators

$$Resilience\ Loss = \int_{t_0}^{t_1} (100\% - Q(t))\,dt$$

Functionality infrastructure/systems

Do & Jung, 2018; Izzaddoost et al., 2021

$$Resilience = \frac{AADT * 365 - ANAF}{AADT * 365} * V * T$$

Annual number of vehicles affected (ANAF)

Hazard likelihood (T)

Vulnerability to identified consequences (V)

Herrera et al, 2017

$$\mathfrak{R}_{\varphi}(t_r|e^j) = \frac{[\varphi(t_r|e^j) - \varphi(t_d|e^j)]}{[\varphi(t_0) - \varphi(t_d|e^j)]} \quad \forall e^j$$

Zhou, 2019

e^j : *disruptive event*

$\varphi(t_r)$: *System performance at* t_r

How to define and calculate resilience?

Attribute-based Approach

Resilience could also be measured in road agencies in terms of potentials (Hollnagel et al., 2018)

Potential to respond: being able to react correctly to any threats and hazards

Potential to monitor: monitor all signals from internal and external environment that may affect an organization's performance

Potential to learn: being able to draw conclusions from experience

Potential to anticipate: being able to predict future developments and in particular potential disruptions

Hollnaget et al., 2018

Absorptive capacity: ability of the system to absorb shocks and stresses and maintain normal functioning

Restorative capacity: ability of the system to recover quickly following a shock or stress and return to normal functioning

Equitable access: ability of the system to provide opportunity for access across the entire community during a shock or stress and during undisrupted times

Adaptive capacity: ability of the system to change in response to shocks and stresses to maintain normal functioning

Weilant & Strong, 2019

These metrics evaluate the level of resilience pre-event and are useful to diagnose various aspects of a road network or agency organization

How to define and calculate resilience?

Topology-based Approach

$$Resilience =$$ Comparison of two topological metrics at two different times (pre- and post-events)

Examples of topological metrics: network maximum eccentricity (Schintler et al., 2007), average shortest path (Berche et al., 2009), average node degree (Zhang et al., 2015), network size (Aydin et al., 2018)

These metrics represent the structure of a network in a graph-based environment. That allows decision makers to evaluate a transportation asset’s topological structural importance within the whole road network before and after disruptions

“**Edge betweenness centrality** is defined as the number of the shortest paths that go through an edge in a graph network” (Girvan and Newman, 2002)

$$\text{EB}(e) = \sum_{v_i \epsilon V} \sum_{v_j \epsilon V} \frac{\sigma_{v_i v_j}(e)}{\sigma_{v_i v_j}}$$

- Combination of all pair of nodes that belongs to V
- Number of shortest between node vi and node vj
- Number of shortest paths *between node vi and node vj which go through e*

“**Node Closeness Centrality** is the reciprocal of the average shorthest path distance to node *n* over all other reachable nodes”

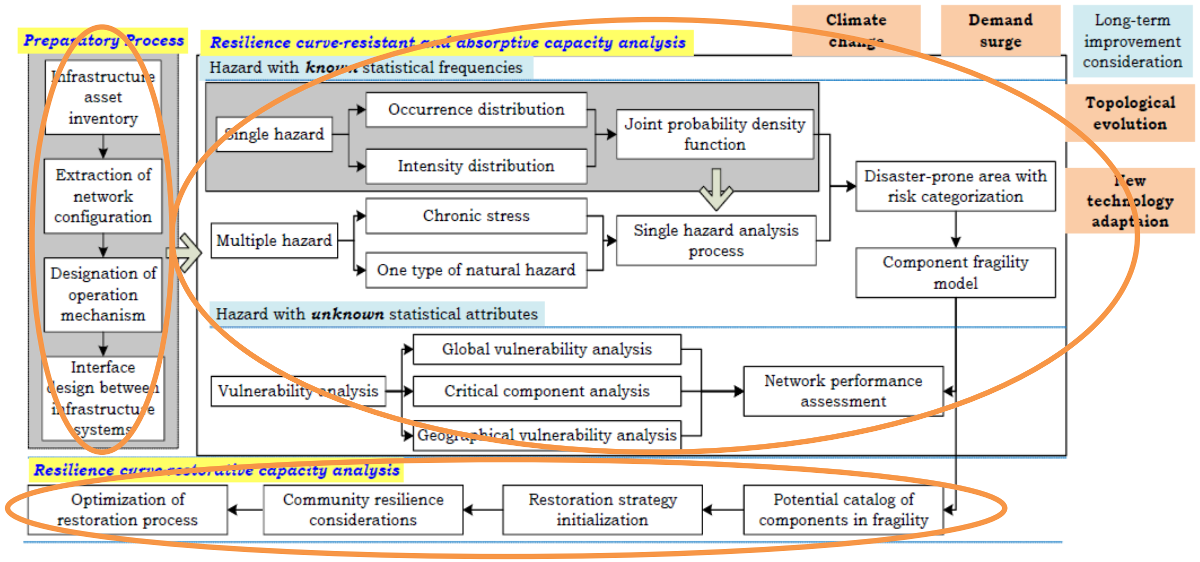
$$\text{C}(n) = \frac{n-1}{\sum_{v=1}^{n-1} d(v,n)}$$

- Distance from *n* to every other node
- Shortest path distance between *v* and *n*

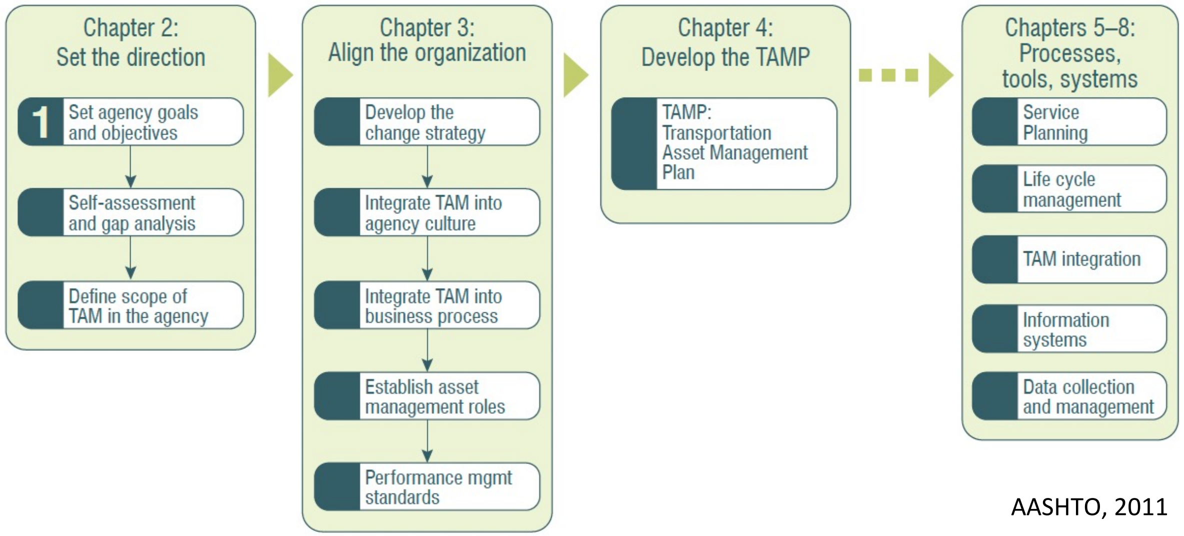
Integration Methods

Frameworks

- Input Data
- Processes
- Results & output data



Yang et al., 2019



AASHTO, 2011

Red dashed lines indicate areas where risk management should be integrated into the framework (Meyer et al., 2012)

Integration at the decision-making process

- Risk and Resilience index/matrix
- Cost benefit
- Expected consequences modeling
- Multi-criteria analysis

Risk and Resilience Indices/matrices

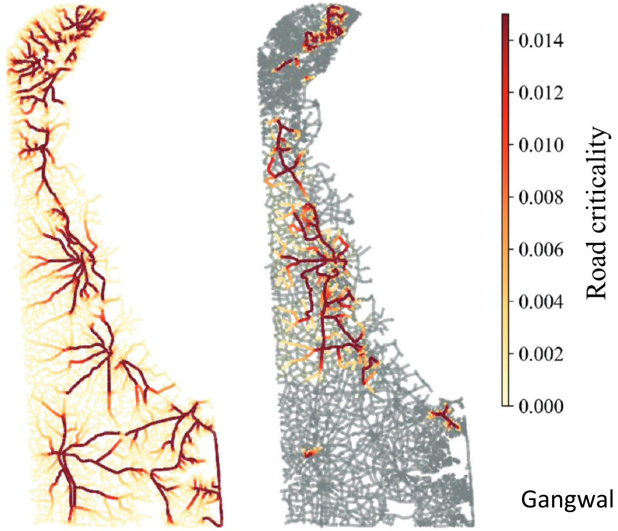
Decision making is based on the prioritization of risk indices or matrices only. Decisions are made based on each asset's score

$$RPN = Occurence\ x\ severity\ x\ significance$$

RPN → Risk Priority Number

significance → Strategic importance of each asset

Chang et al, 2020



(a) Critical roads before flooding

(b) Critical roads after 100-year flood

Gangwal et al, 2022

$$IR = \Pr \times C$$

- IR: Risk Index
- Pr: Occurrence Probability
- C: Consequences

$$V = f\{ESTADO, VEN\}$$

- V: Vulnerability Index
- STATE: Condition of road infrastructure
- VEN: Vulnerability to natural hazards

$$C = IES \times V \times E$$

$$IES = \{IA, ISP, TMDA, JER\}$$

- IES: Strategic Importance
- IA: Accessibility Index
- ISP: Economic Road Relevance Index
- TMDA: Traffic Index
- JER: Road Hierarchy Index

$$E = f\{IE, L_A, L_T, NE\}$$

- IE: Exposition Index
- L_A: Length of road link affected by natural events
- L_T : Total Length of road link
- NE: Number of natural events

Echaveguren and Sanhueza, 2011

Macro Zone	Region	Route	IR
North	Arica and Parinacota	A-15	52,8
		Route 11-CH	47,7
	Antofagasta	Route 1	41,0
		Route 21-CH	41,0
		Route 23-CH	41,0
		B-207	29,0
		Route 27-CH	27,0
	Atacama	Route 31-CH	46,3
		Route 5	39,0
		C-35	36,6
		C-17	30,0
Center	Valparaiso	Route 68	34,7
		F-30-E	31,0
		F-800	24,4
	Metropolitana	G-25	50,0
		G-421	27,0
		G-21	32,0
		G-251	25,0
		G-355	20,0
	O'Higgins	H-448	32,0
		H-328	23,0

Ranking of different road segments according to risk index for further prioritization

Cost Benefit analysis

$$TR_i = \sum_{j=1}^{8} S_{ji} \times \sum_{u=1}^{U} \left(\frac{(1-DA_i)^{u-1} \times DA_i}{(1+\tau)^{u-1}}\right)$$

(BENEFITS)

Alshboul et al, 2021

Social Impacts:

1) Highway accidents
2) Emergency Access route
3) Tourism and indistry
4) Isolated locations
5) Traffic restrictions
6) Complaints
7) Post measure construction activities
8) Congestion/detour due to post-measure work

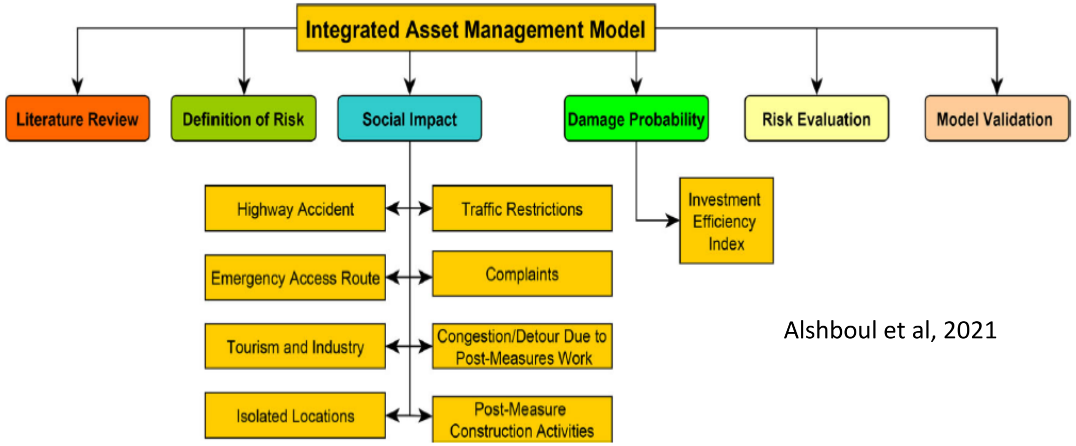
$$CT_i = \theta CT_i + \gamma CT_i$$

(COST)

γCT_i: Congestion/detour cost (USD) incurred during countermeasure construction in the current deteriorated state

θCT_i: Countermeasure cost in the current deterioration state (USD)

This method involves the combination of a risk/resilience index change (benefit) and the cost of each intervention



Alshboul et al, 2021

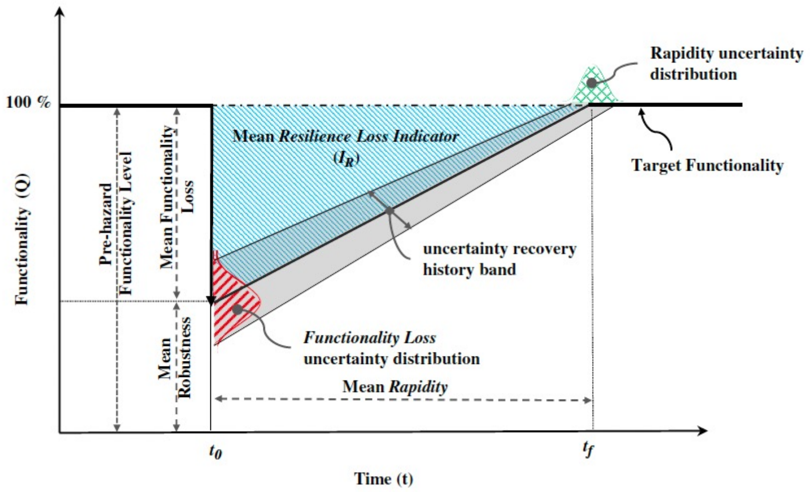
Highway users' expected costs caused by highway facilities' malfunction in service for pavements, bridges, and dangerous slopes are defined as risk

Expected consequence modeling to decision making

This method is based on a stochastic analysis of consequences. Decisions are made based on the expected benefits they may produce

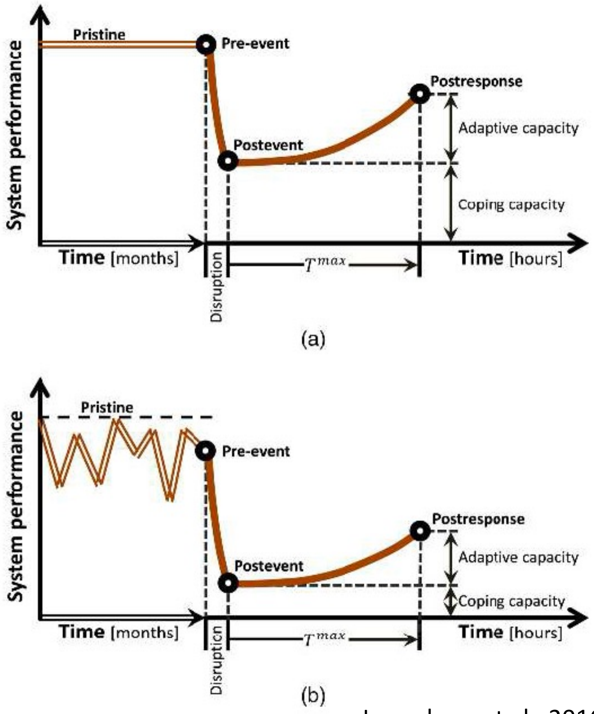
- Probabilistic hazard analysis
- Resilience assessment considers the effect of normal stressors such as normal weather and vehicles load
- Performance models are evaluated in a long-term period of analysis and consider annual deterioration/occurrence models

Uncertainty modeling



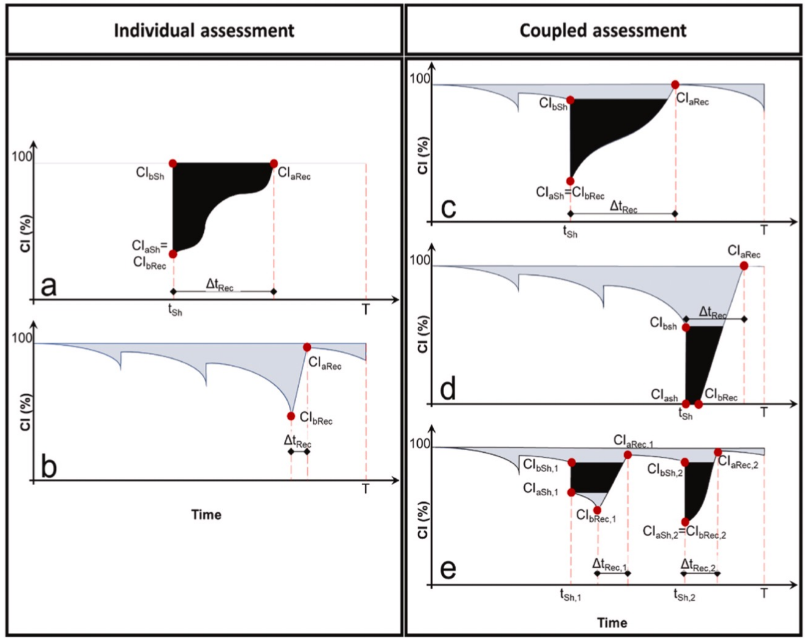
Salem et al., 2020

Pre-event conditions



Levenberg et al., 2016

Coupled effect (hazard + stressors)



Izzaddoost et al., 2021

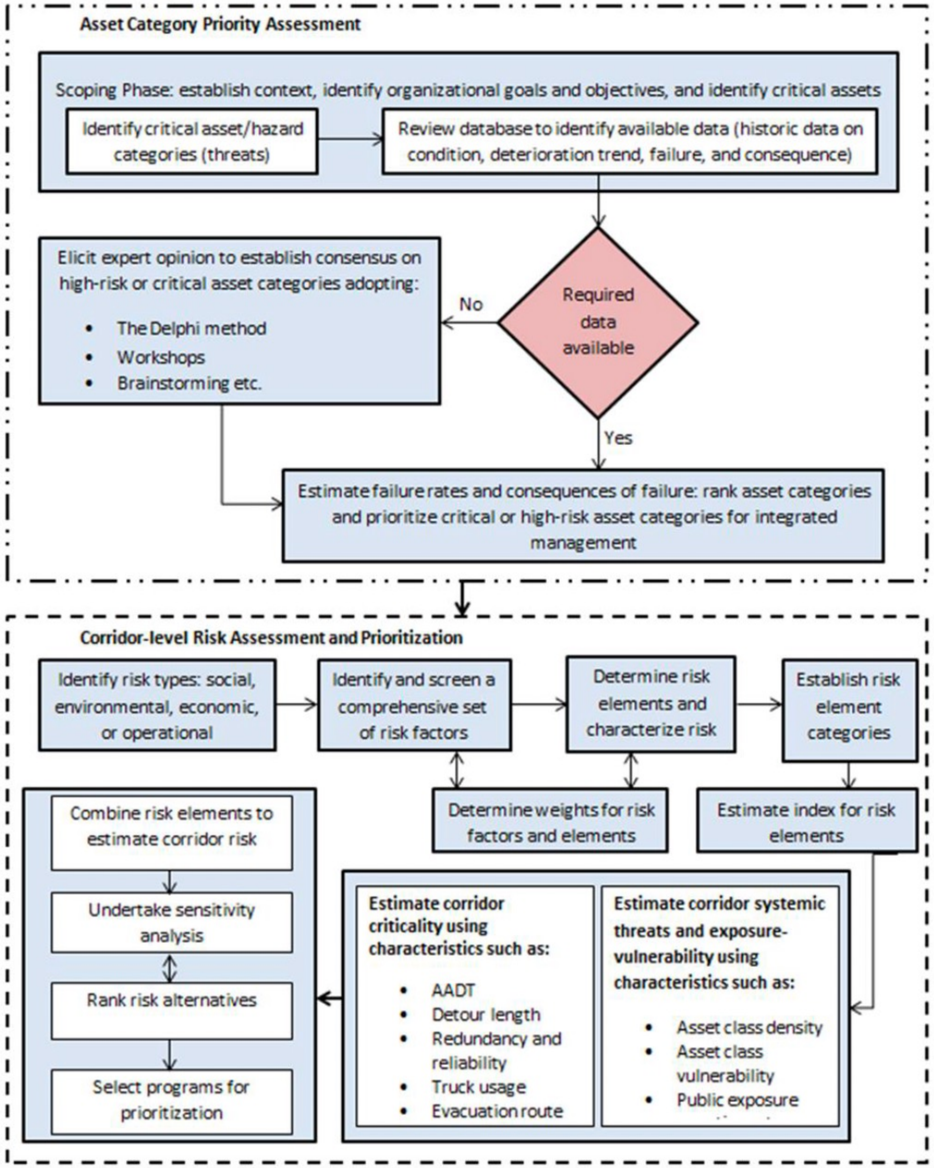
Multi-criteria Analysis

This method considers a set of different dimensions for the decision-making process and they are integrated in a multi dimensional index for subsequent prioritization

$$C_i = \sum_{i,j=1}^{n,m} W_j R_{i,j}$$

- W_j: Relevance of each criterion j
- $R_{i,j}$: Normalized rating of the segment i for criterion j
- C_i: Overall score of each segment i

- The Delphi Method
- Expert Opinion
- Statistical Analysis



Boadi, 2015

Limitations of the current state of Art and Practice

- Lack of comprehensive guidelines
- Limited indirect loss models
- Lack of standardised resilience and risk modelling approaches
- Integration of asset pre-existing conditions into resilience or risk assessments
- Impact of climate change on natural hazard event frequency

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