

Developing a System Model to Evaluate Risk of Urban Transportation Network

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Introduction and Statement of the Problem

- ✓ High seismicity in Iran and the need for an efficient transportation network for emergency response
- ✓ Rapid urban expansion and growth of metropolitan areas
- ✓ Lack of a comprehensive, system-based approach for evaluating risk and interrelations among parameters
- ✓ Limited attention to social parameters in previous transportation risk studies

1



Influx of private and emergency vehicles on the streets

2



Physical damages to transportation network infrastructure

3



Road blockages caused by debris from roadside structures

4

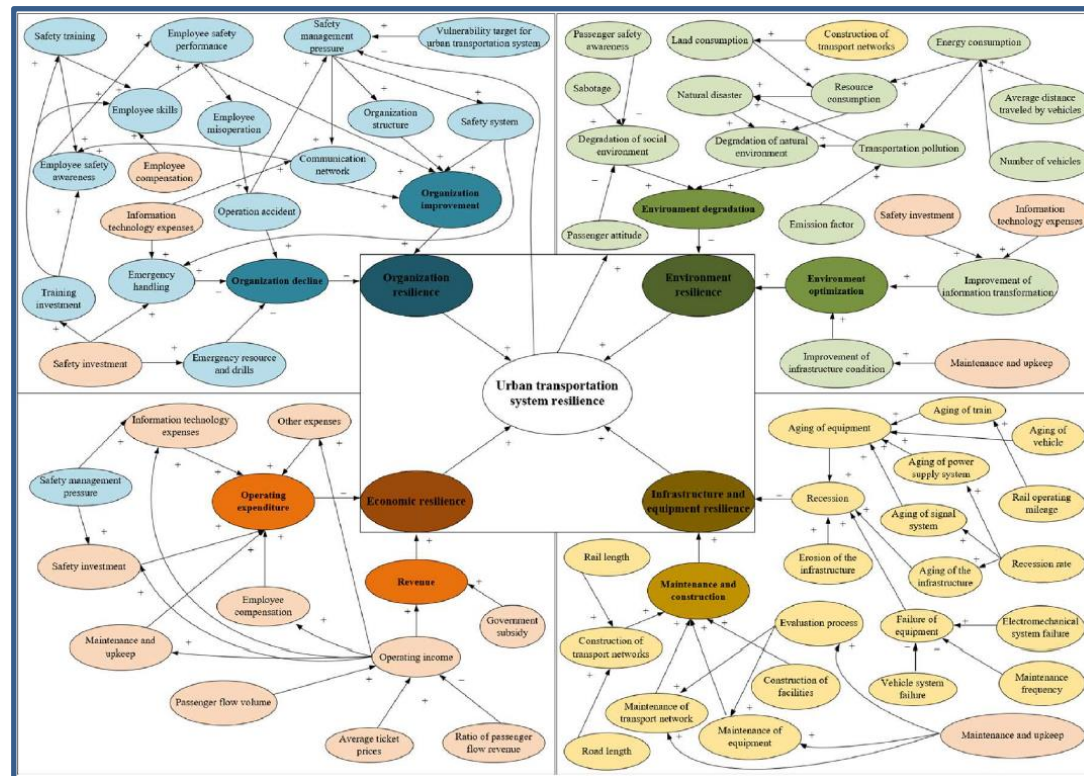


Road blockages caused by debris from roadside structures

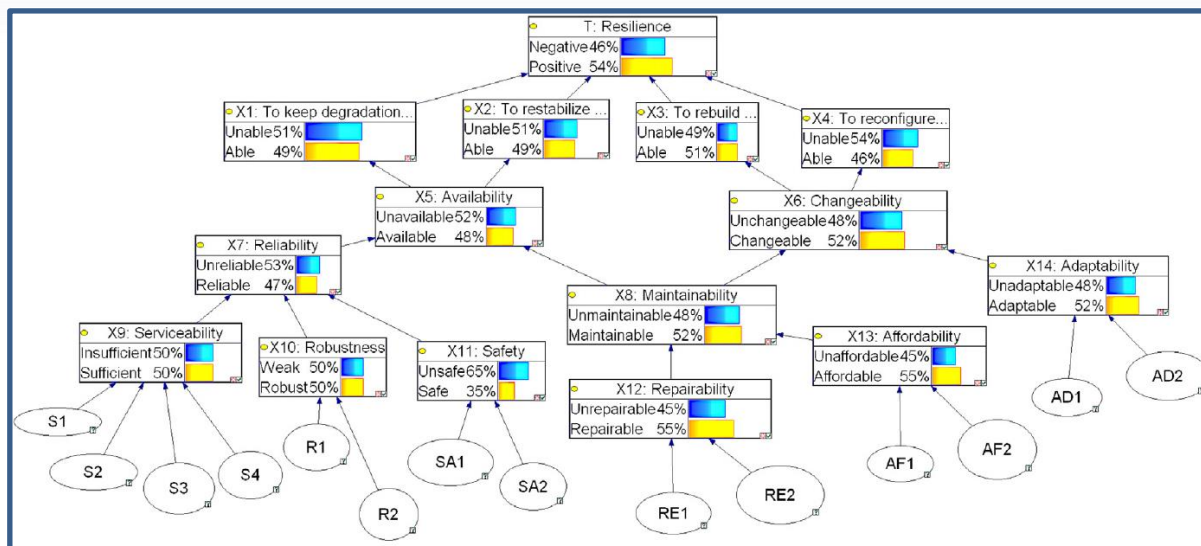
Main Research Objectives

- ✓ To develop a comprehensive **system-based model** for evaluating transportation network risk and enhancing the resilience of urban systems.
- ✓ To assess the **cascading effects** of individual parameters on overall system performance and risk.
- ✓ To analyze how different parameters affect transportation network **risk** and **goals**.
- ✓ To integrate **social parameters** and **human behavioral** factors into the transportation risk assessment model.
- ✓ To provide a **decision-support tool** for authorities to prioritize the most effective risk reduction interventions.

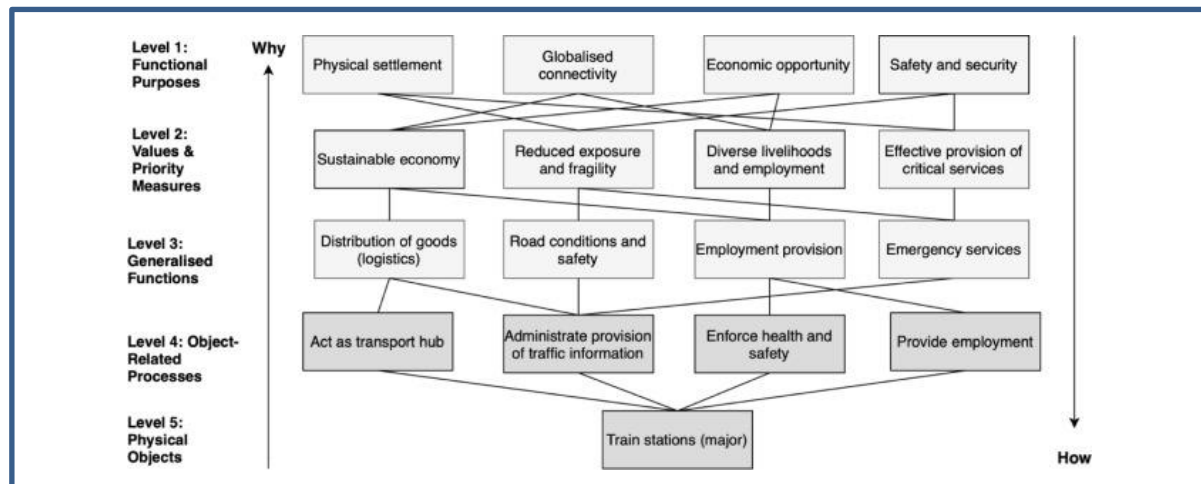
Sample of past studies on system approach methods



System dynamic method (Wang et al. 2024)



Bayesian network model (Tang et al. 2020)



Graph based model (McClymont et al. 2024)

Author	Objectives	Methodology	Considered parameters/metrices	Challenges
Tang et al. (2020)	Evaluate long-term resilience in urban transportation systems using a systems-based Bayesian Network Model (BNM)	Using BNM by combining graph theory and probability theory	1 -Function Layer (Macro-level) 2-Quality Layer (Meso-level) 3-Factor Layer (Micro-level)	-Data Limitations -Ignorance of vulnerability of transportation infrastructures
Wang et al. (2024) [10]	Assess resilience of urban transportation systems (UTS) over the long-term using a system dynamics (SD) model	System dynamic model	1-Organization Resilience 2- Environment Resilience 3- Economic Resilience 4-Infrastructure and equipment resilience	-The SD model relies on expert judgments and historical data, introducing potential biases . - Complexity of Interdependencies
Chopra et al. (2016) [7]	Assess transportation network resilience using graph-based metrics	Graph based method	Network connectivity metrics (small-world properties, clustering coefficient, global efficiency) and resilience measures (redundancy, fracture coefficient)	-limited real-time data - The study focuses exclusively on the metro system.
Zhang et al. (2015)	Analyze the impact of network topology on transportation resilience	Graph based method	Connectivity (alpha, beta, gamma indices), network topology (grid, hub-and-spoke, small-world), disruption scenarios, recovery strategies.	- Computational complexity - The study focuses mainly on topological features while neglecting other key parameters

Existing Challenges in Previous Studies

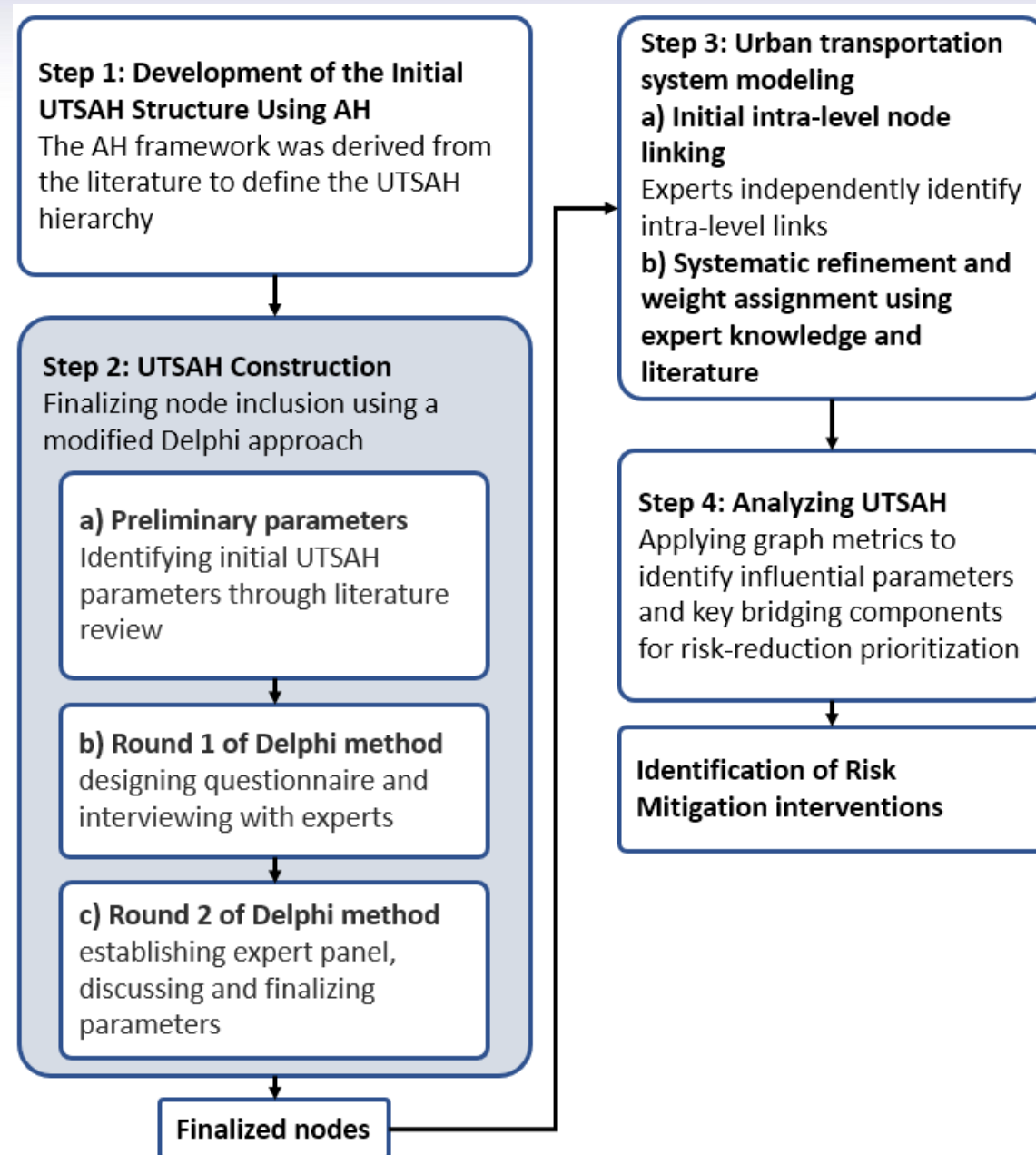
Dynamic methods require **extensive data, complicated computations**, and face modeling and validation challenges

BNM-based studies face **uncertainties in expert judgments** and require complementary methods to address these limitations.

Graph-based studies also have limitations, as they mainly focus on transportation **topology** while neglecting other critical aspects of network risk and resilience.

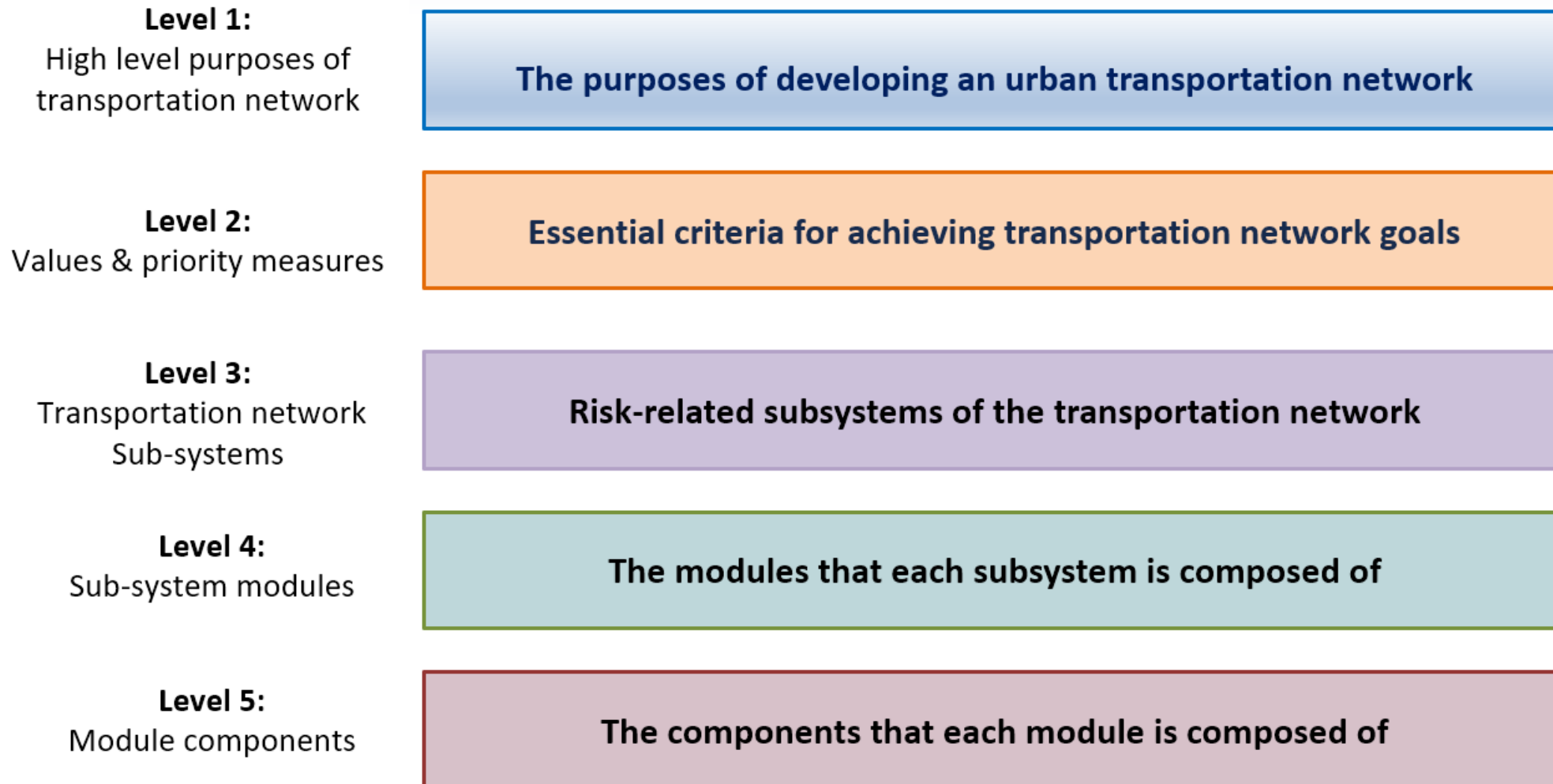
Several critical components of the transportation network are overlooked in each study.

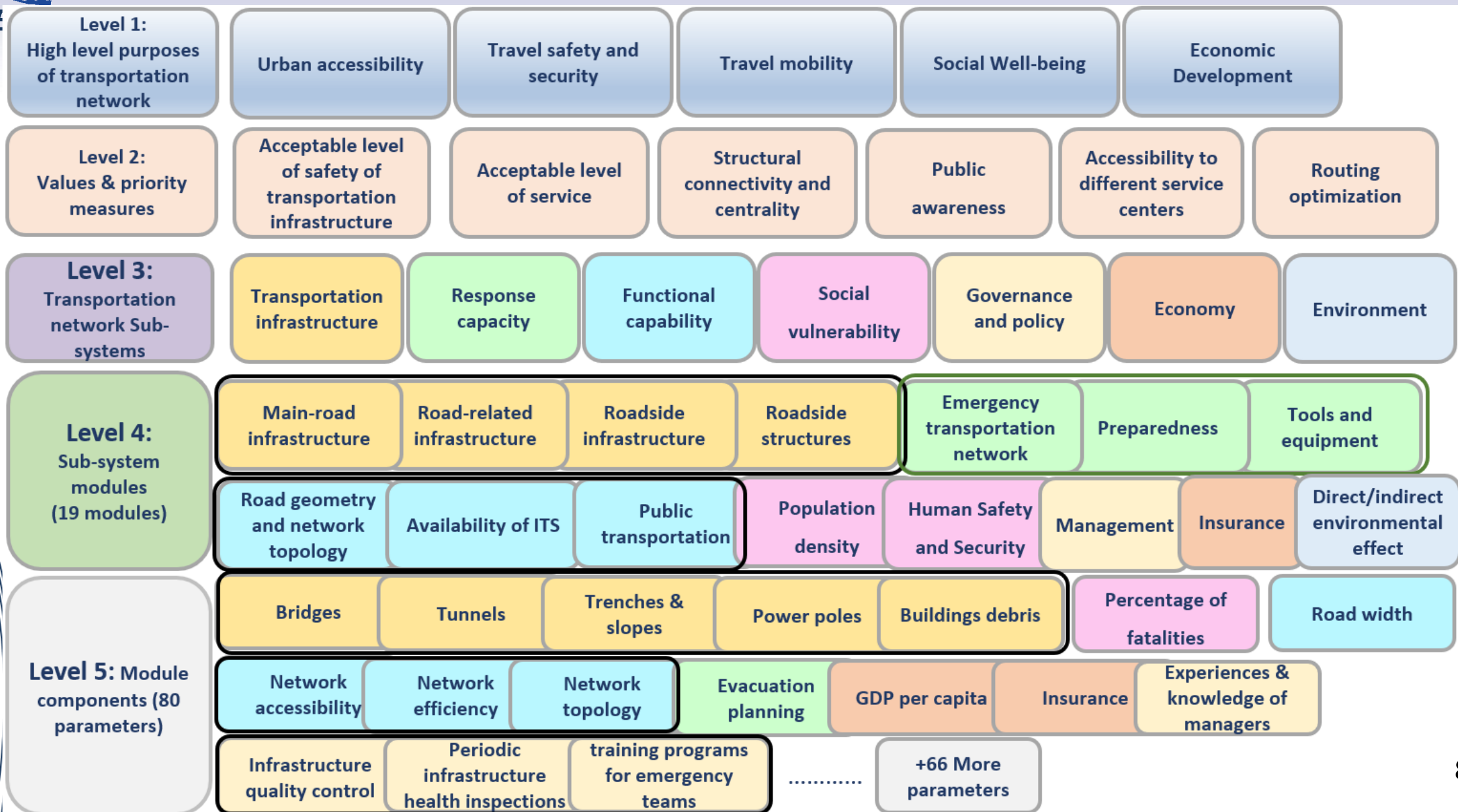
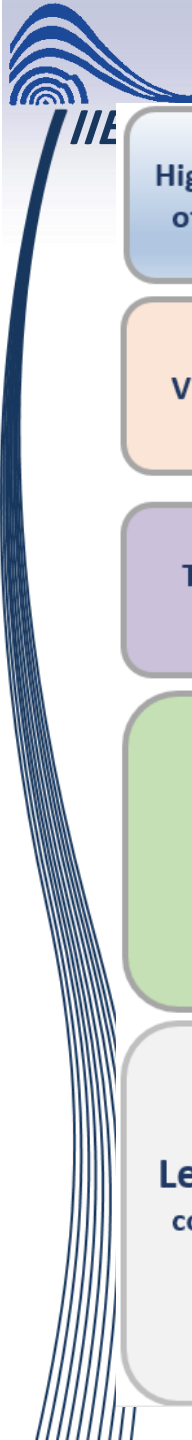
phase I: Proposed System Model for Transportation Risk Evaluation

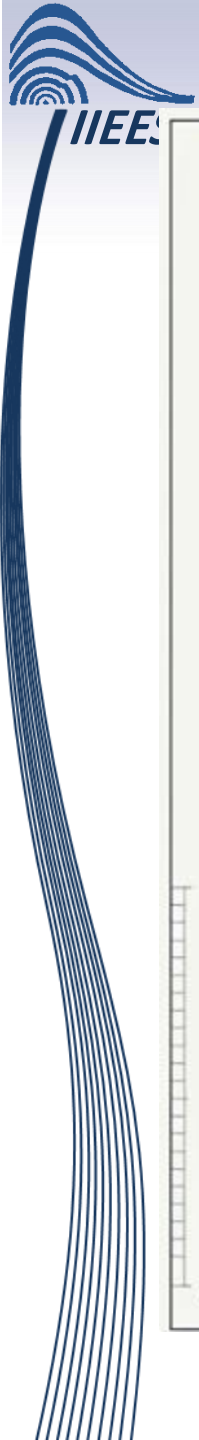


Main Steps of Developing the System Model

Step 1- Identifying Urban Transportation System Abstraction Hierarchy (UTSAH) by forming an expert group







UTSAH: The Urban Transportation System Abstraction Hierarchy

LEVEL 1: GOALS

Abstract societal purposes

LEVEL 2: CRITERIA

Normative benchmarks

LEVEL 3: SUBSYSTEMS

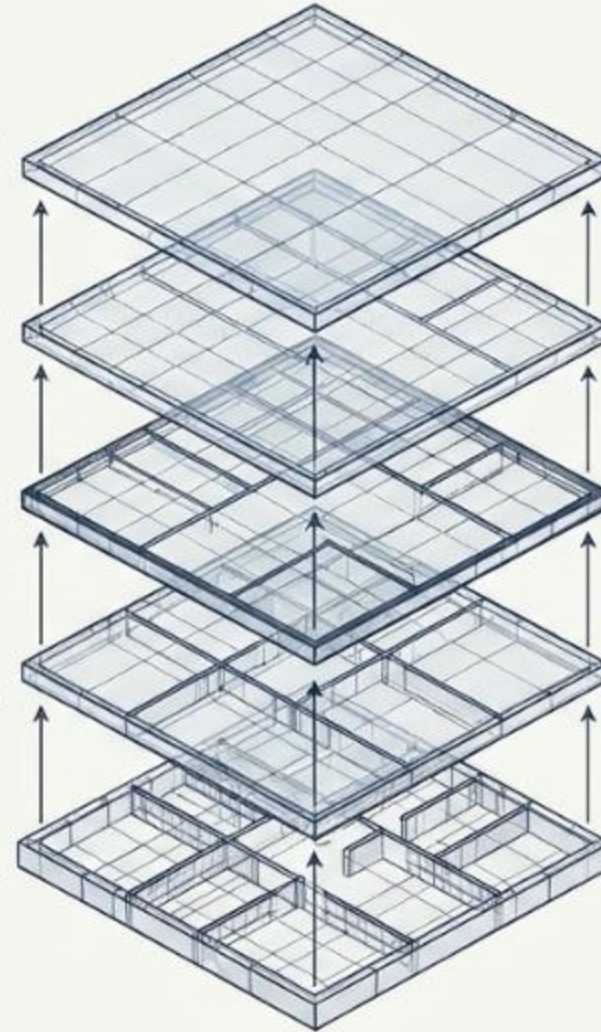
7 dimensions of risk—the primary diagnostic layer

LEVEL 4: MODULES

Functional component groups

LEVEL 5: PARAMETERS

78 quantifiable, localized data points

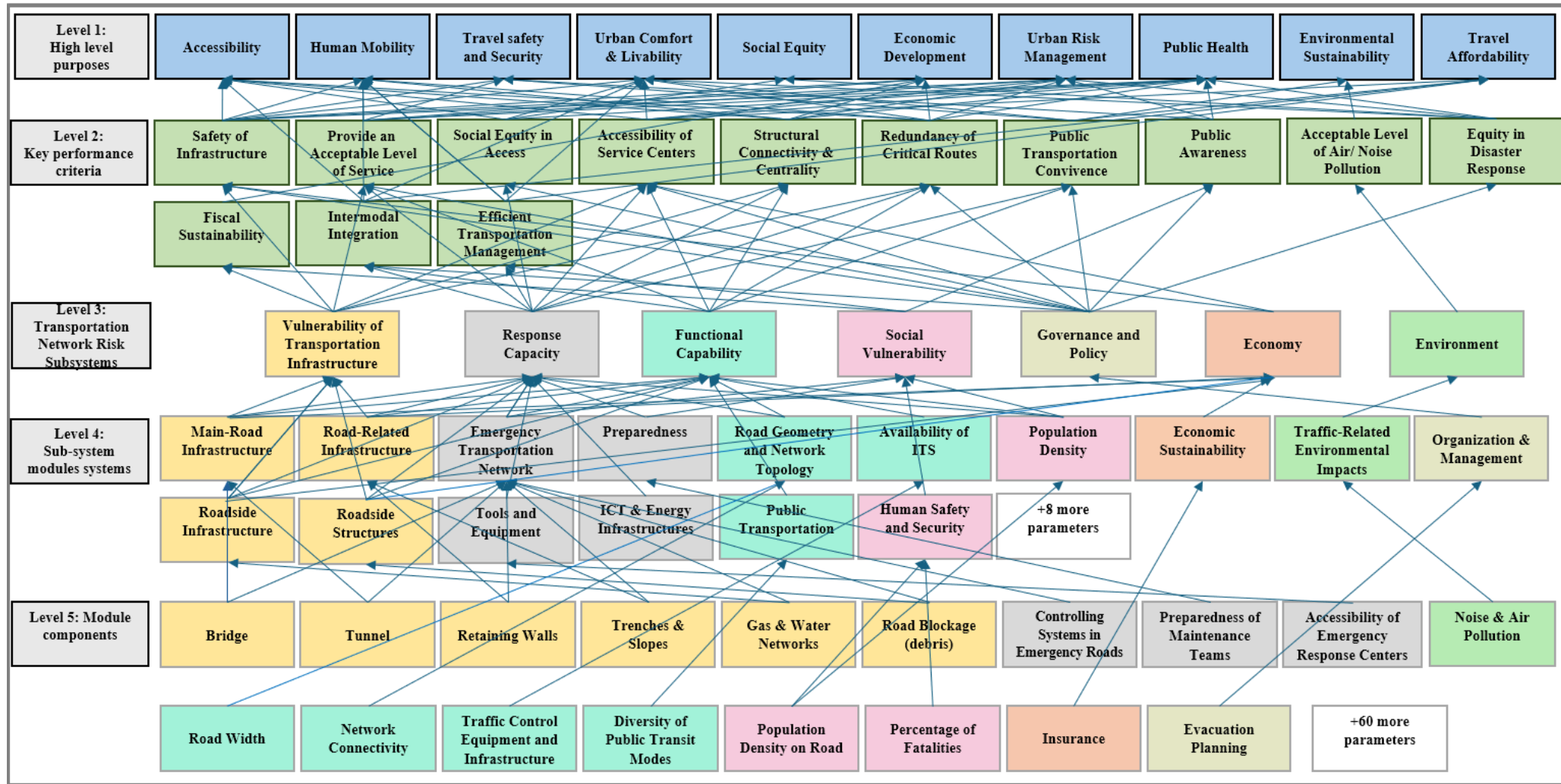


131 parameters
interlocked in a
directed graph.

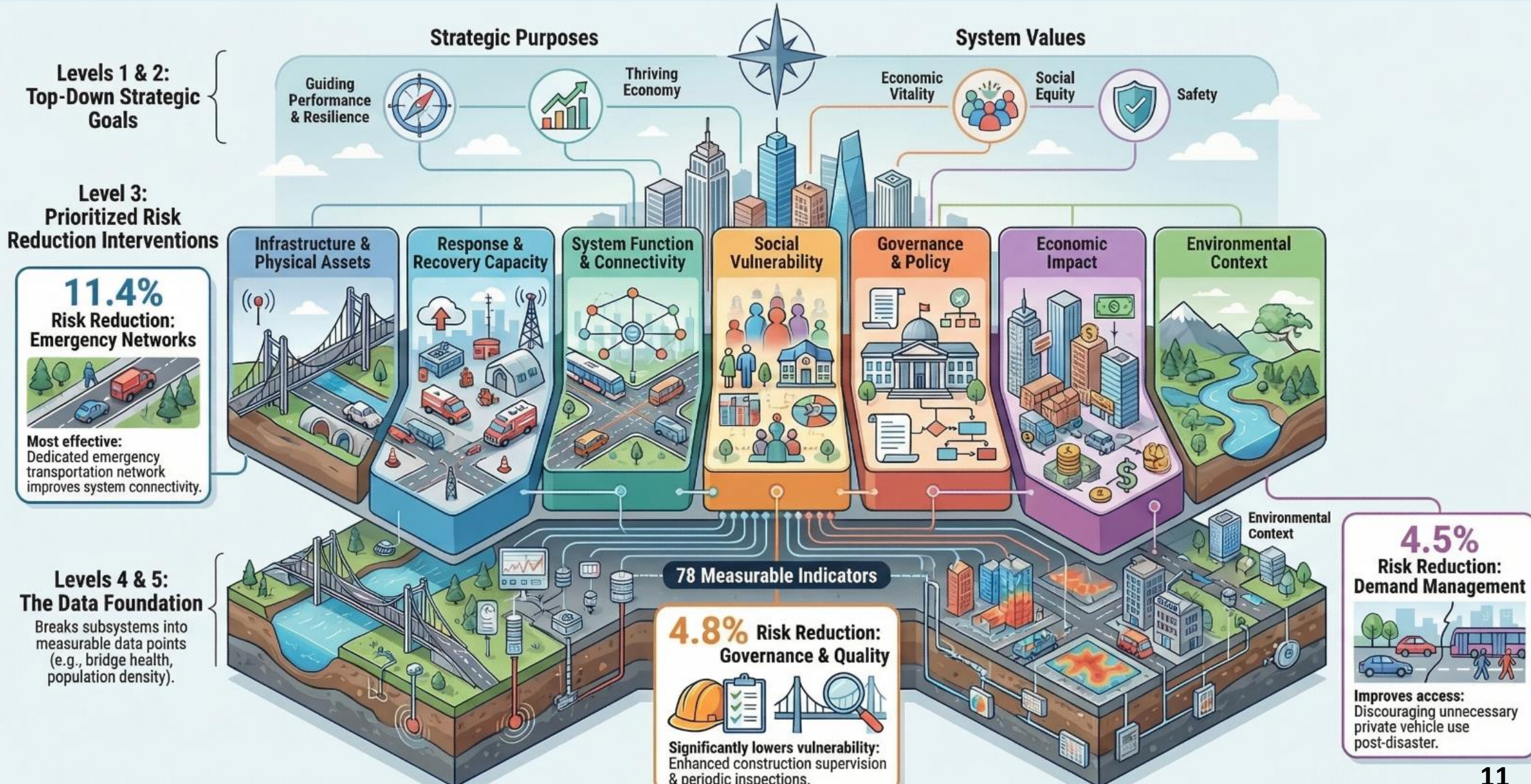
Damage at the
base (Level 5)
does not exist in
isolation; it
bubbles up
through the
system's
hierarchy.

Main Steps of Developing the System Model

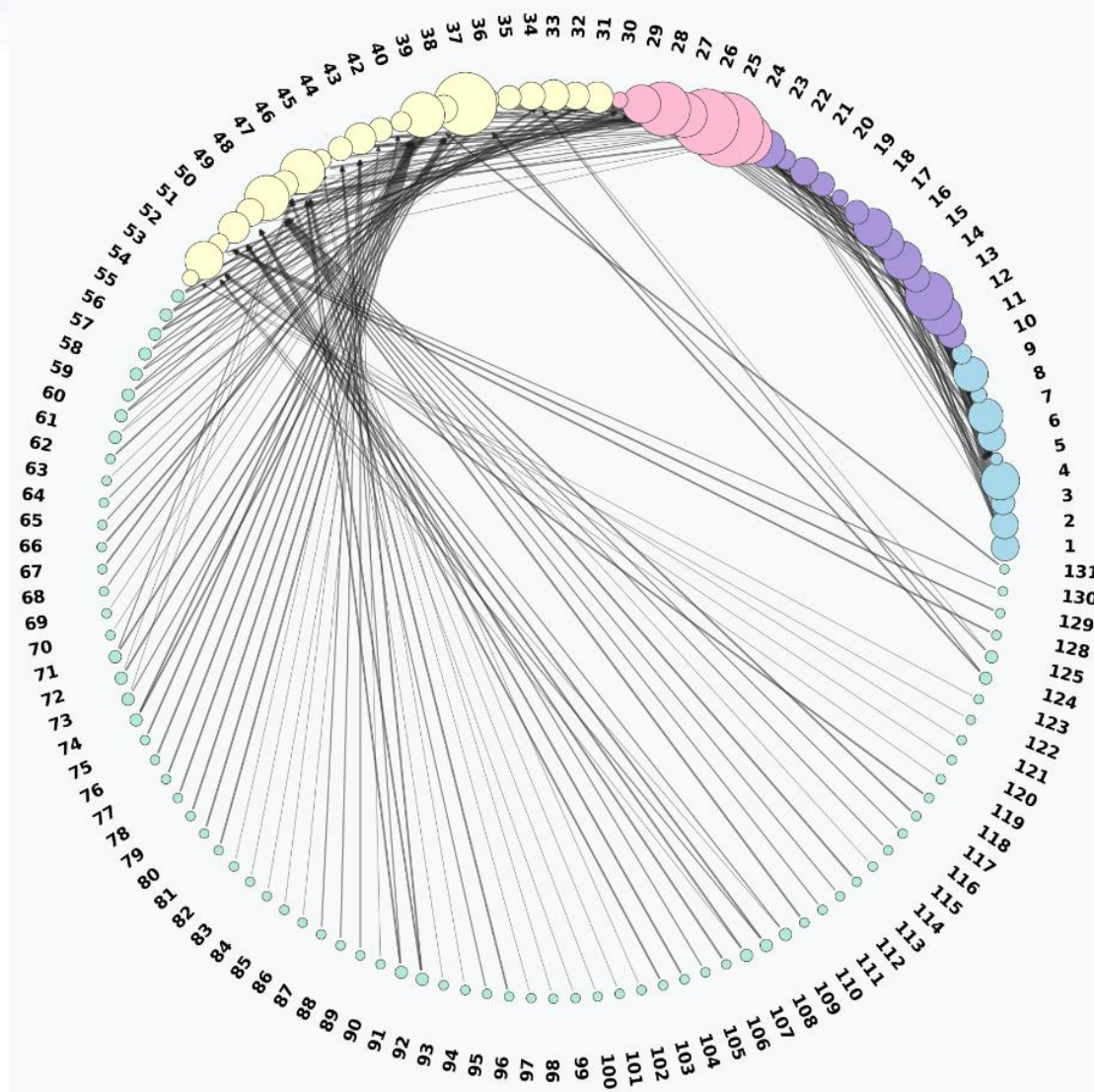
Step 3. Constructing **inter-level adjacency matrices** with **expert-assigned weights** and **mapping the system** to visualize critical pathways and interdependencies.

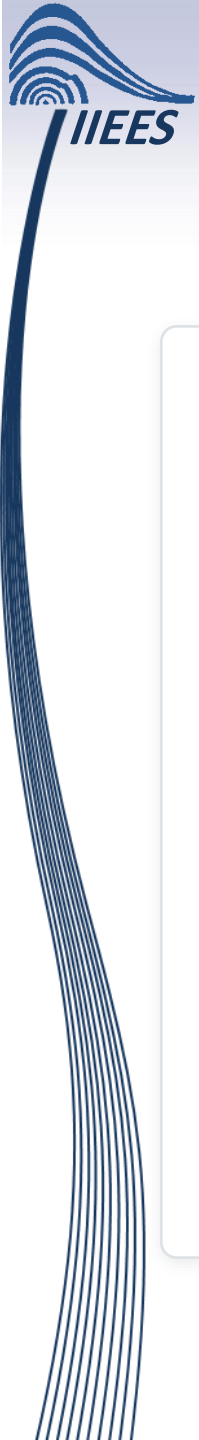


Urban Transportation Network Abstraction Hierarchy (UTSAH)



System Model of Transportation Network Parameters





Step 4: Two centrality measures, two system roles

Eigenvector Centrality (EC)

A node is more influential if it connects to other influential nodes — capturing recursive, system-wide reinforcement.

- Outgoing EC → dominant risk drivers (where disruption originates)
- Incoming EC → convergence points (where influence accumulates)

$$C_E(x) = (1/\lambda) \sum W(x, x') \cdot C_E(x')$$

Betweenness Centrality (BC)

Measures how often a parameter lies on the shortest paths connecting other parameters — a transmission intermediary.

- High-BC parameters govern how risk spreads, not where it originates
- Their failure fragments the network and disrupts coordination

*Shortest paths through
weighted influence links*

Outgoing eigenvector centrality: dominant risk drivers

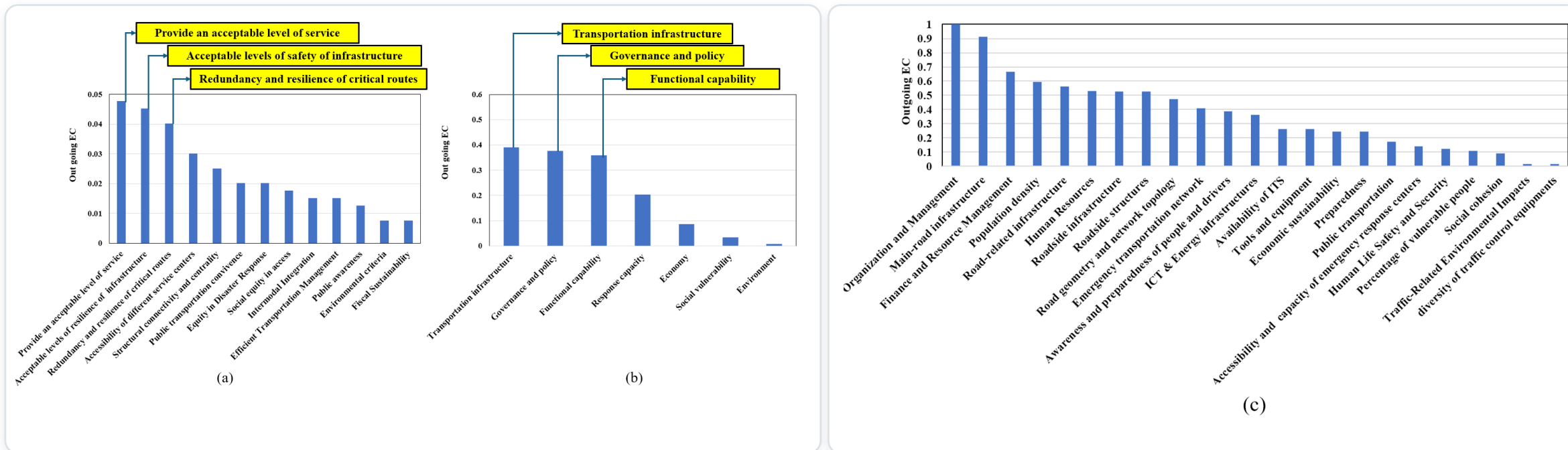


Fig. 5 — Outgoing EC of model parameters (levels 2–4)

- Level 2: acceptable level of service, infrastructure safety, and route redundancy
- Level 3: transportation infrastructure, governance and policy, functional capability
- Level 4: organization & management and main-road infrastructure score highest — key sources of risk propagation

Incoming eigenvector centrality: convergence points

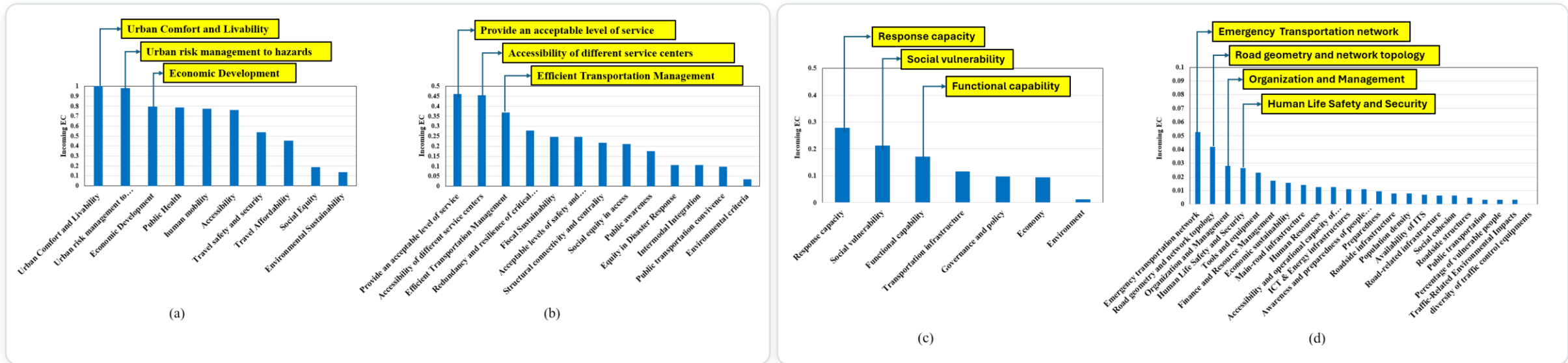


Fig. 6 — Incoming EC of model parameters (levels 1–4)

- urban comfort and livability and urban risk management to hazard are the purposes with highest incoming EC
- Social equity and environmental sustainability are the purposes (for developing transportation network) with lowest incoming EC.

Critical transmission chokepoints

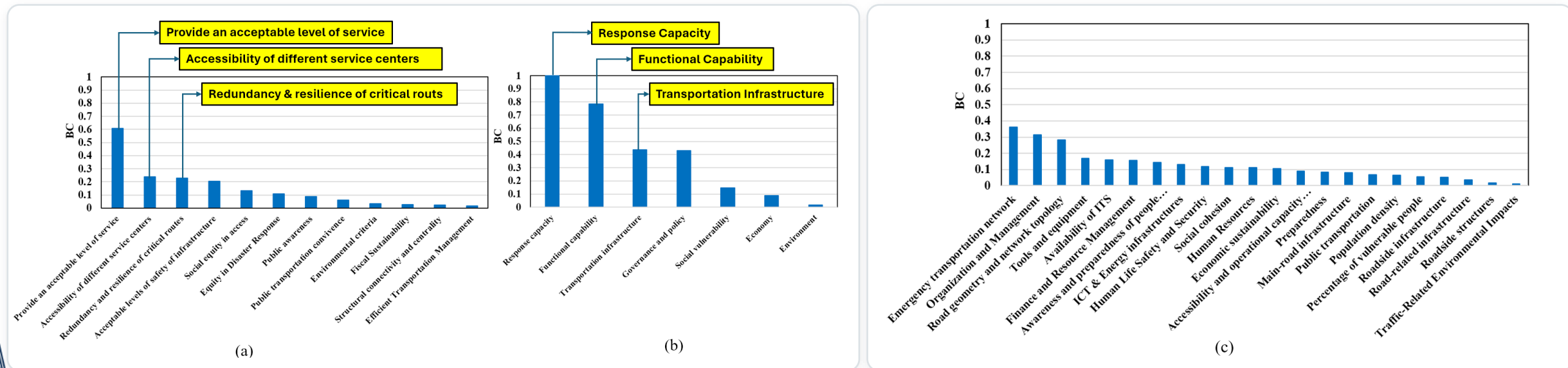


Fig. 7 — Betweenness centrality of model parameters (levels 2–4)

- Emergency transportation network, organization & management, and road topology are key structural chokepoints
- Their disruption can fragment coordination and constrain alternative routing system

Monte Carlo sensitivity analysis (N = 100)

Link weights were perturbed within bounded limits; robustness was quantified via Spearman's rank correlation (ρ). Values shown as median (P5–P95).

Level	Node Number	Incoming EC (Med)	Incoming EC (P5)	Incoming EC (P95)	Outgoing EC (Med)	Outgoing EC (P5)	Outgoing EC (P95)	BC (Med)	BC (P5)	BC (P95)
1	10	0.85	0.66	0.95	-	-	-	-	-	-
2	13	0.67	0.51	0.89	0.83	0.68	0.93	0.32	-0.12	0.60
3	7	0.93	0.86	0.96	0.86	0.75	0.96	0.96	0.89	1.00
4	23	0.82	0.70	0.89	0.79	0.67	0.87	0.88	0.84	0.97
5	78	-	-	-	0.61	0.48	0.71	-	-	-

Rankings are not very sensitive to moderate weight perturbation — centrality structure is primarily governed by hierarchical topology, not exact expert weights.

HAZARD PROPAGATION — SCENARIO 1

Bridge degradation cascades upward through the hierarchy

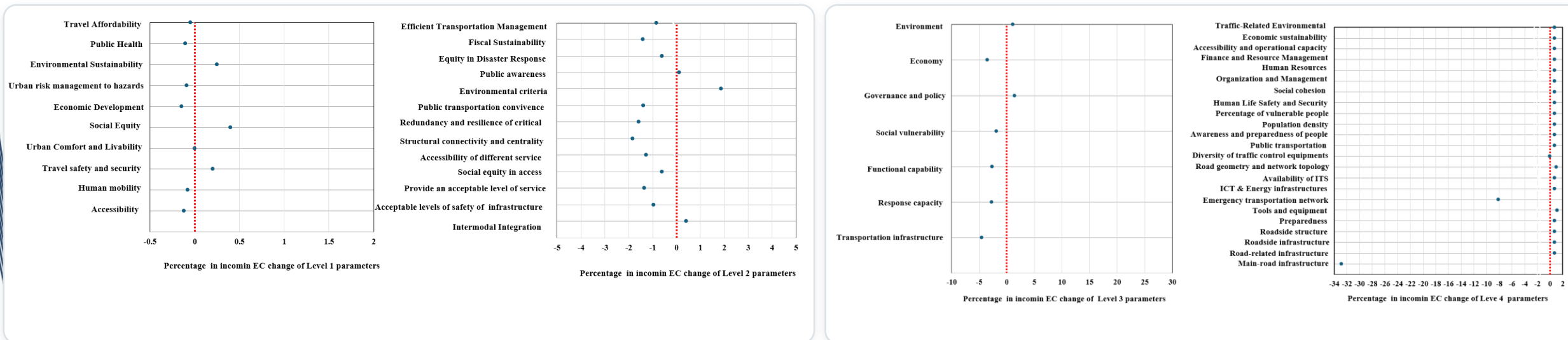


Fig. 8 — Impact of reducing bridge weight (near-zero) across levels 1–4

- Level 4: main-road infrastructure -32.84%; emergency transportation network -8.14%
- Level 3: transportation-infrastructure vulnerability -4.54%, economy -3.50%, response capacity -2.71%
- Level 1 purposes shift only gradually — buffered by multiple parallel support pathways

HAZARD PROPAGATION — SCENARIO 1

Visualizing the cascade of bridge degradation

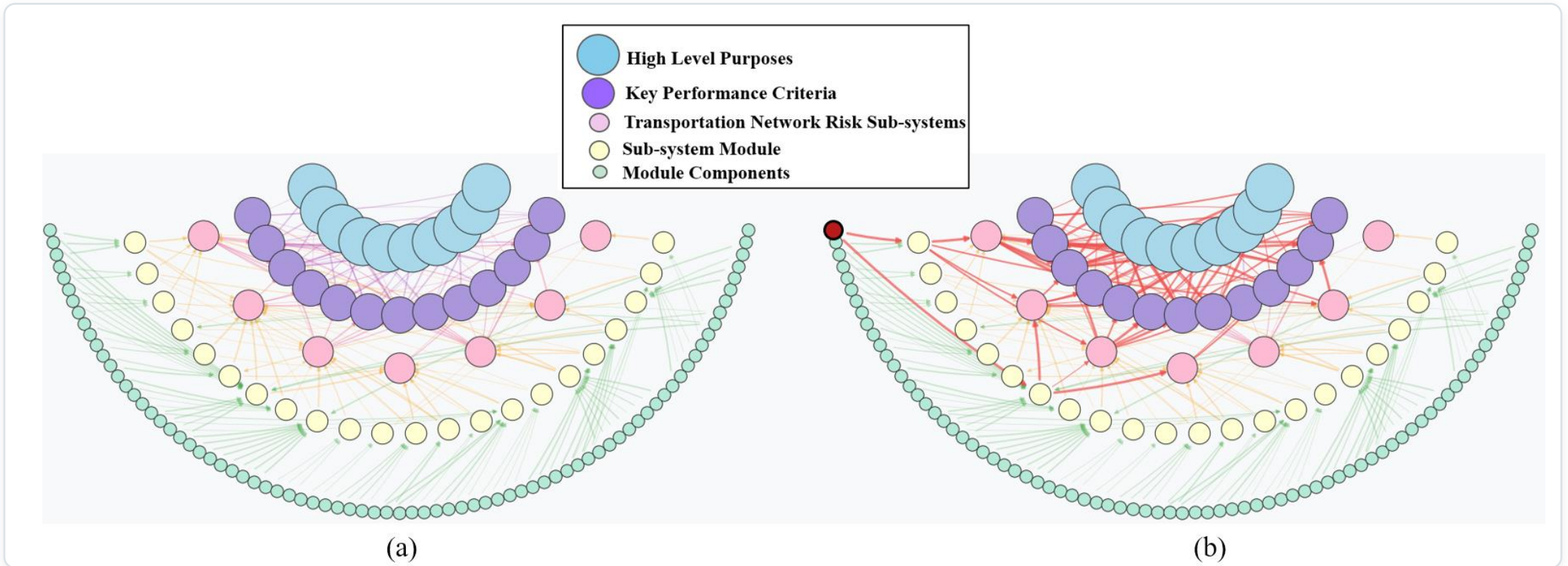
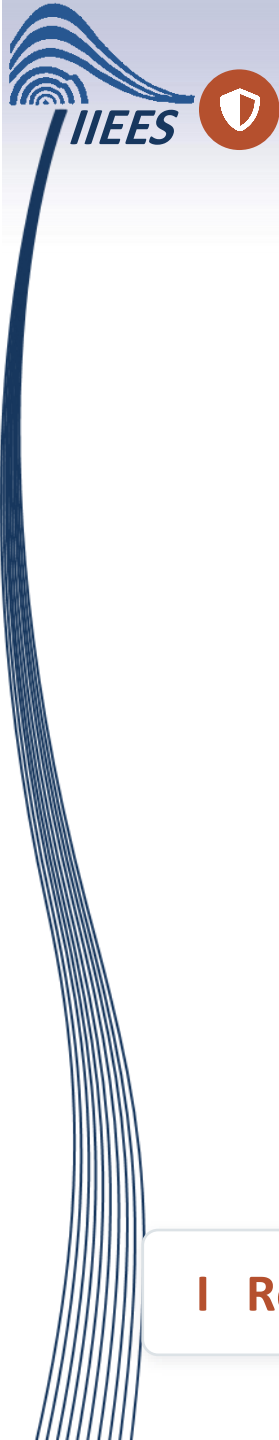


Fig. 9 — (a) Baseline configuration (b) cascading effects of bridge degradation, highlighted in red



From centrality metrics to candidate strategic interventions

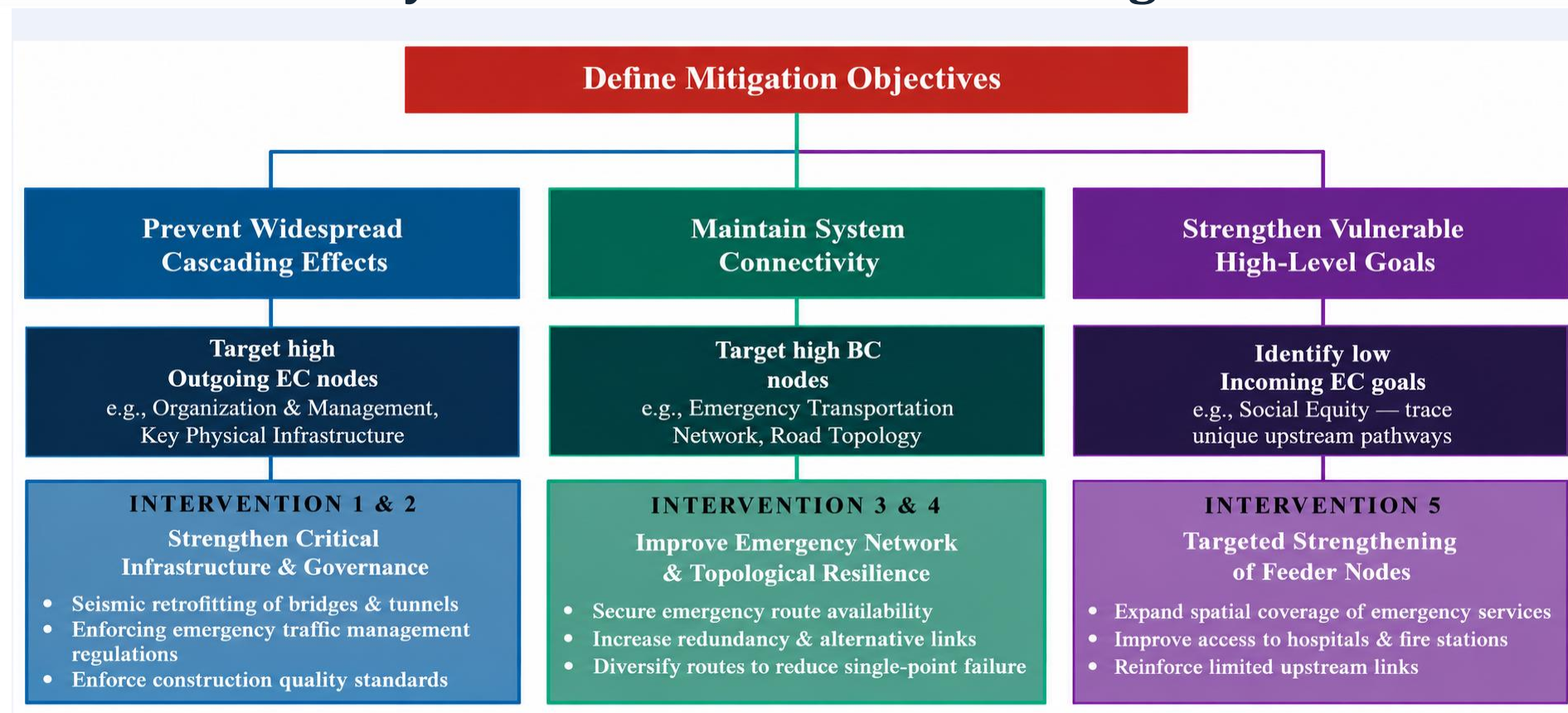
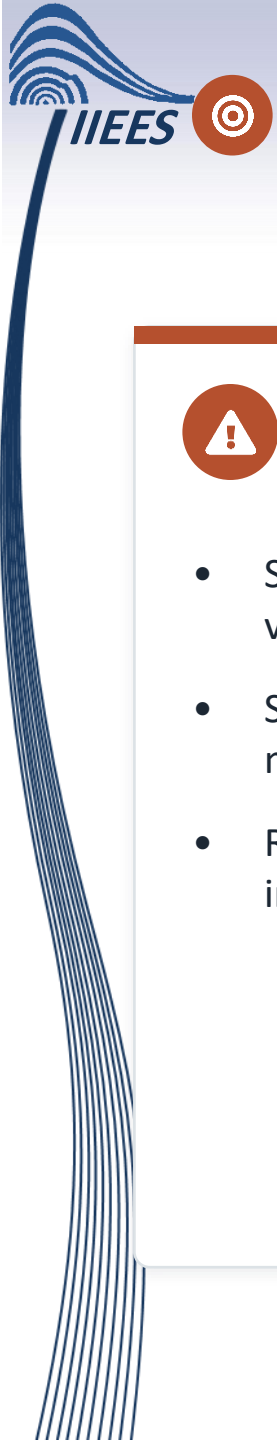


Fig. 11 — Graph-based framework for identifying risk-mitigation interventions

I Reduce cascading effects

II Preserve connectivity

III Strengthen weak goals



Three strategic intervention priorities



Category I

Reduce cascading effects

- Seismic retrofitting of vulnerable bridges & tunnels
- Strengthen organization & management capacity
- Regular infrastructure inspections & quality control



Category II

Preserve connectivity

- Control systems & signage on emergency roads
- Public awareness of emergency-route priority
- Increase route redundancy and network topology



Category III

Strengthen weak goals

- Add emergency service centers in underserved zones
- Upgrade access roads to critical service centers
- Designate multi-purpose secondary emergency hubs

Phase II: Risk Quantification

Implementing the UTSAH Framework for Seismic Risk Assessment

131

Model Parameters

5

Hierarchical Levels

7

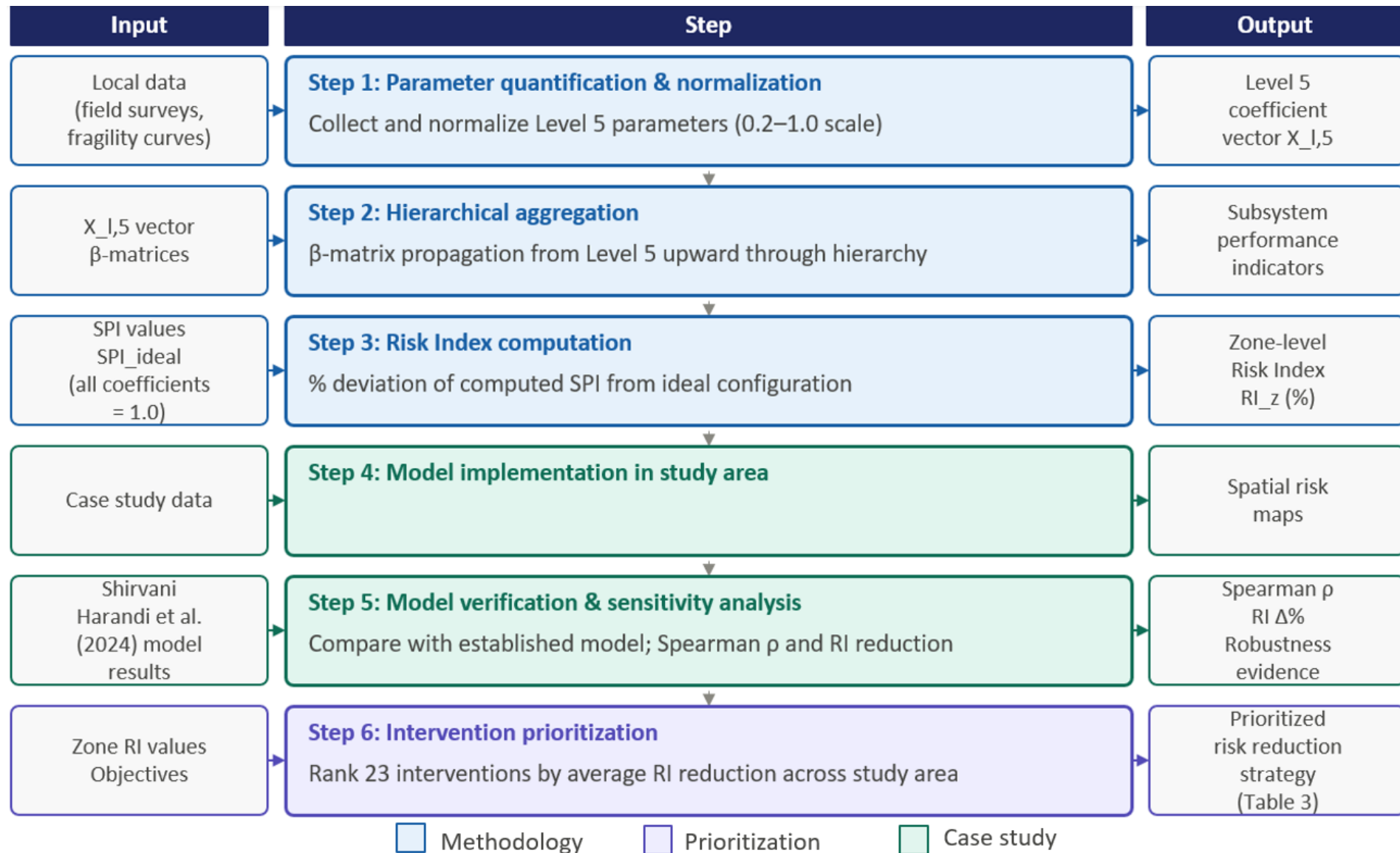
Risk Subsystems

22

Interventions Evaluated

Building on EC & BC analysis → Quantifying zone-level seismic risk → Prioritizing interventions

Methodology Overview



Step 1 (phase II): Parameter Quantification & Normalization

Each parameter evaluated using a criterion reflecting local conditions

Normalization Scheme (for bridges as example)

Interval	Coeff.
1 (worst)	0.2
2	0.4
3	0.6
4	0.8
5 (best)	1.0

Bridge Vulnerability

Method:
Fragility curves
(Avsar et al.; HAZUS)

Metric:
No. of collapsed /
damaged bridges per zone

Pavement Damage

Method:
Syner-G fragility curves

Metric:
% road length in extensive
damage state per zone

Population Density on Roads

Method:
Occupancy model
(Coburn et al.)

Metric:
People per hectare
at time of earthquake

Social Cohesion

Method:
Questionnaire-based
survey (Delphi-validated)

Metric:
Qualitative scale:
Very high → Low

Road Blockage

Method:
GIS-based model
(Mansouri et al.)

Metric:
% completely blocked
roads per zone

Evacuation Facilities

Method:
Coverage radius
index (CRI)

Metric:
Available open space
per person (m²)

Physical Infrastructure
Social Vulnerability

Response Capacity
Governance & Policy

Functional Capability
Economy & Environment

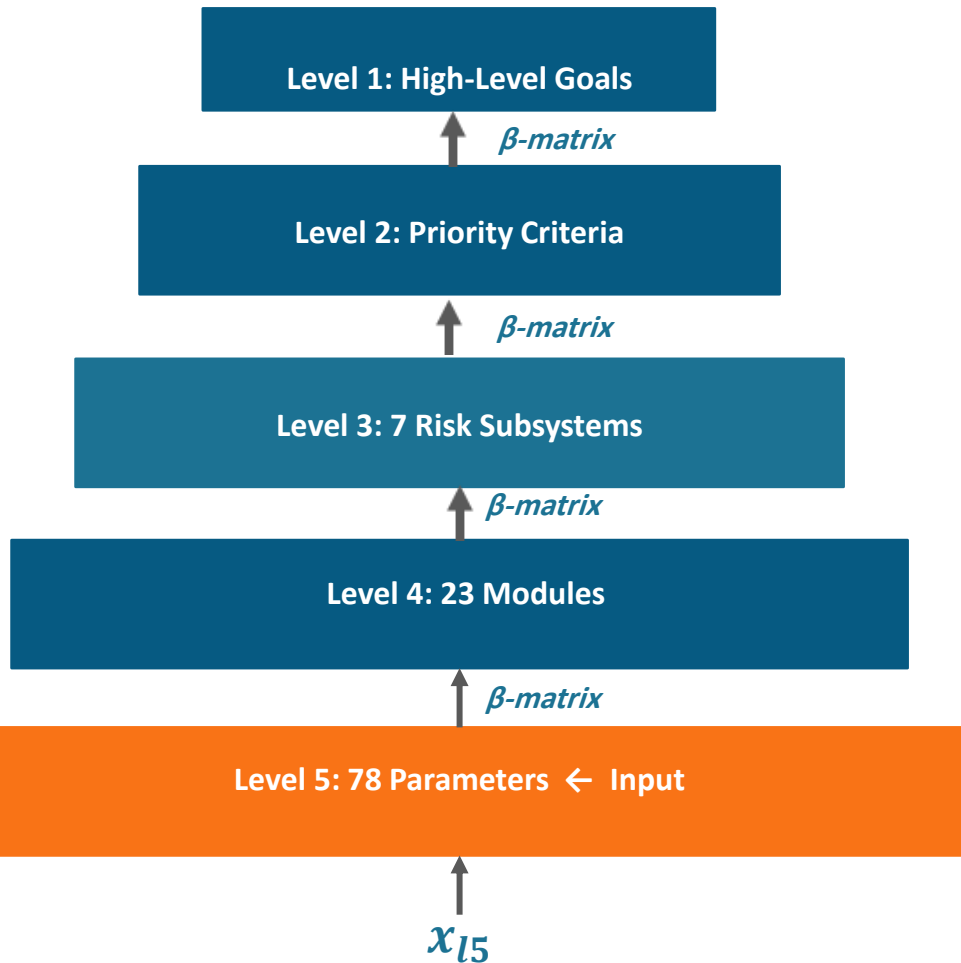
Step 1 (phase II): Parameter Quantification Criteria (Sample)

Each parameter assigned weight-reduction coefficients based on local conditions

Parameter	Criterion / Method	1.0 (Best)	0.8	0.6	0.4	0.2 (Worst)
Bridges	No. collapsed/damaged bridges — fragility curves [1,2,3]	0	1	2	3	>3
Pavement	% road length in extensive damage state — HAZUS & Syner-G [4,5]	0	<5%	5–10%	10–15%	>15%
Evacuation facilities	Available open space per person (m²) [9]	>3.5	3–3.5	2.5–3	2–2.5	<2
ER team preparedness	Questionnaire-based survey	Very high	High	Moderate	Low	Very low
Road width	% roads <9m width / total road length [9]	0	0–10%	10–20%	20–30%	>30%
Network connectivity	Node degree [10]	>2.6	2.45–2.6	2.3–2.45	2.15–2.3	2–2.15
Population density on roads	People/hectare at time of EQ — occupancy model [15]	<10	10–20	20–35	35–50	>50
Evacuation planning	Existence, quality & effectiveness — questionnaire	Comprehensive	Structured	Basic	Limited	Emerging
GDP per capita	Nominal USD [38]	>\$50,000	\$25–50k	\$10–25k	\$2.5–10k	<\$2,500

Step 2: Hierarchical Aggregation via β -Matrices

Damage at Level 5 propagates upward through the hierarchy



Aggregation Formula

$$X_{l,i} = \left(\prod_{k=5}^{i+1} B_{k,k-1} \right) X_{l,5} \quad i = 1, 2, 3, 4$$

$X_{l,5}$ = Level 5 coefficient vector (reduction weights from Step 1)

$B(k,k-1)$ = β -matrix encoding interdependencies between adjacent levels

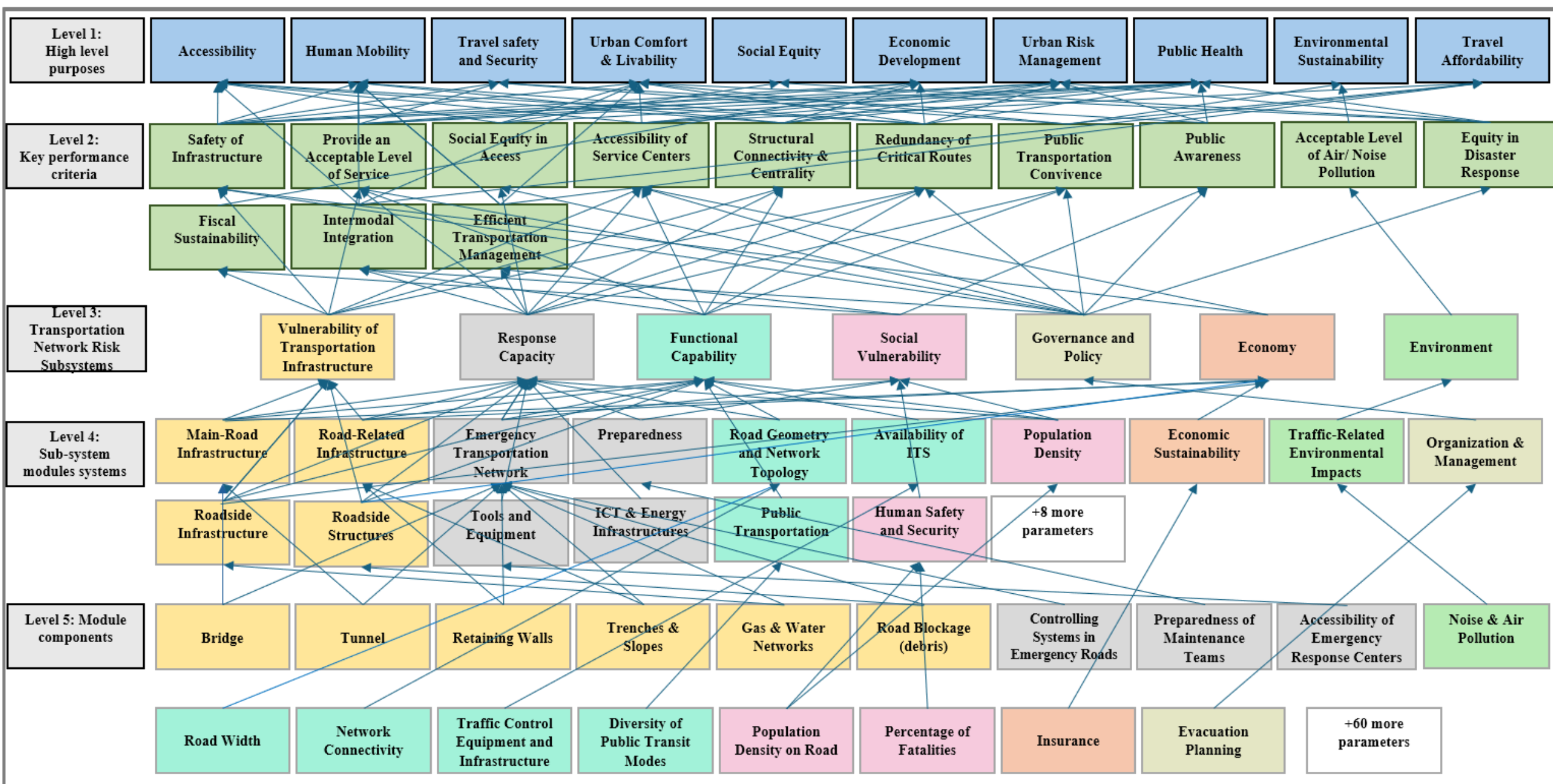
$X_{l,i}$ = aggregated performance vector at Level i

Why β -matrices?

Unlike simple aggregation, β -matrices preserve the cascading structure:

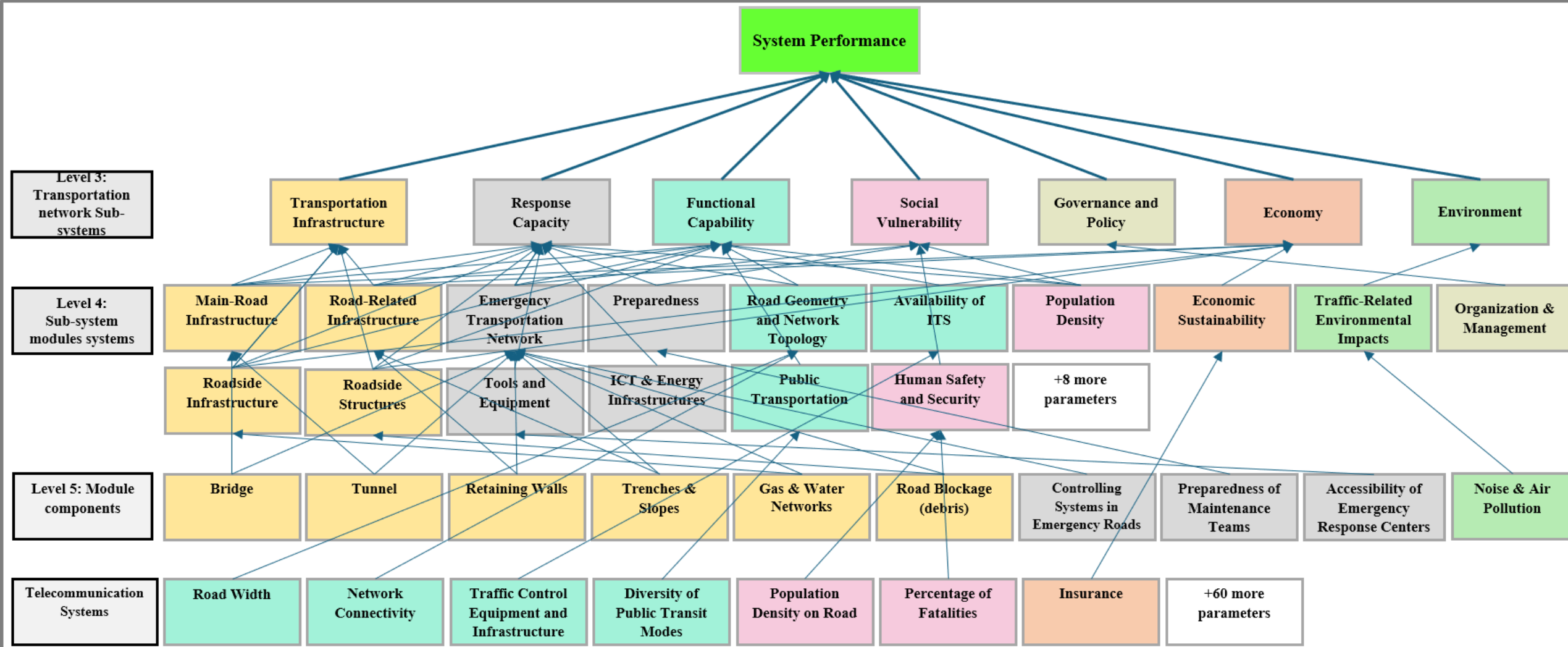
- damage at Level 5 propagates step-by-step, maintaining subsystem traceability.
- This directly connects the EC/BC analysis to quantifiable zone-level risk.
- The β -matrices are derived from the same weighted adjacency matrices.

Example: Bridge damage (L5, coeff=0.2) → Main road infra. degraded (L4) → Infrastructure subsystem weakened (L3) → System performance



Step 3: Risk Index Computation

System performance flowchart



Step 3: Risk Index Computation

% deviation from ideal system performance

System Performance Index (SPI)

$$SPI_z = W^{1 \times 7} \times \left(\prod_{k=5}^4 B_{k,k-1} \right) X_{l,5}$$

$$W^{1 \times 7} = [w_{vul} \ w_{res} \ w_{func} \ w_{econ} \ w_{so_vul} \ w_{gov} \ w_{environ}]$$

Weighted aggregation of 7 subsystem indicators.
Weights derived from the same Delphi expert process used to build UTSAH adjacency matrices.

Risk Index (RI)

$$RI_z = \frac{SPI_{ideal} - SPI_z}{SPI_{ideal}} \times 100$$

SPI_ideal: all Level 5 coefficients = 1.0 (full performance)

**Larger RI → greater departure from optimal → higher seismic risk
Standardized, comparable metric across zones & scenarios.**

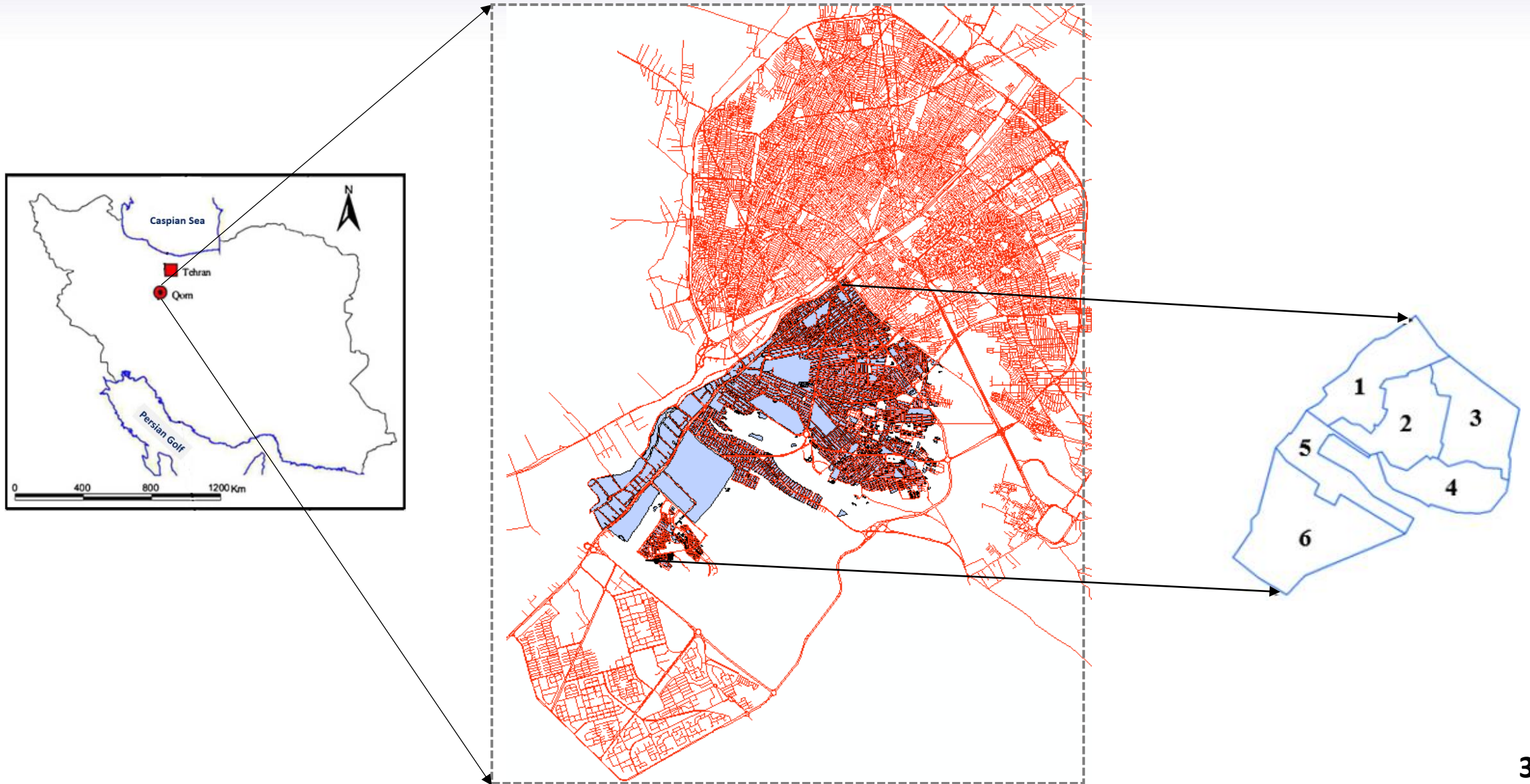
Why exclude Levels 1 & 2?

Level 1 = abstract societal purposes | Level 2 = normative criteria — neither directly quantifiable from earthquake damage data.
Level 3 subsystems are the highest practically measurable tier → directly linked to SPI.

step 4: Implementing model in study area (District 4 of Qom city)



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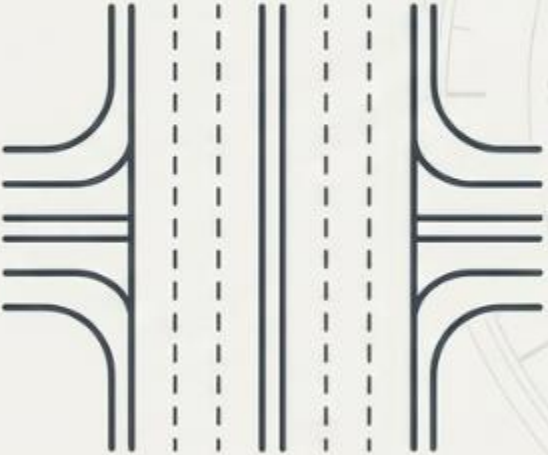
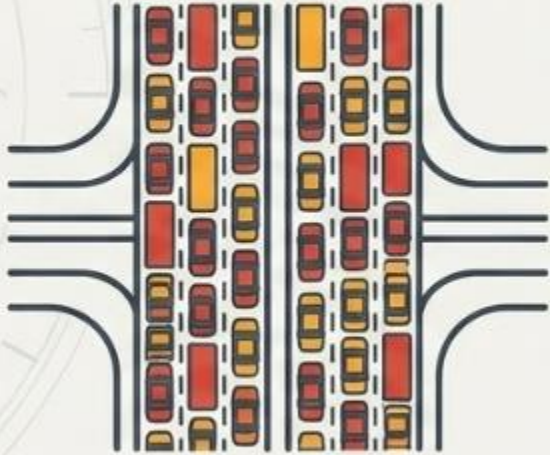


Location of Qom city and study area

Step 4: Implementing Model in the Study Area (District 4 of Qom city)

Considered scenarios

To implement the model in the study area, an earthquake scenario with a return period of 475 years was considered for three different time periods:

Scenario 1	Scenario 2	Scenario 3
02:00 a.m.	12:00 p.m.	06:00 p.m.
		
Low traffic	Moderate traffic	Peak traffic hours

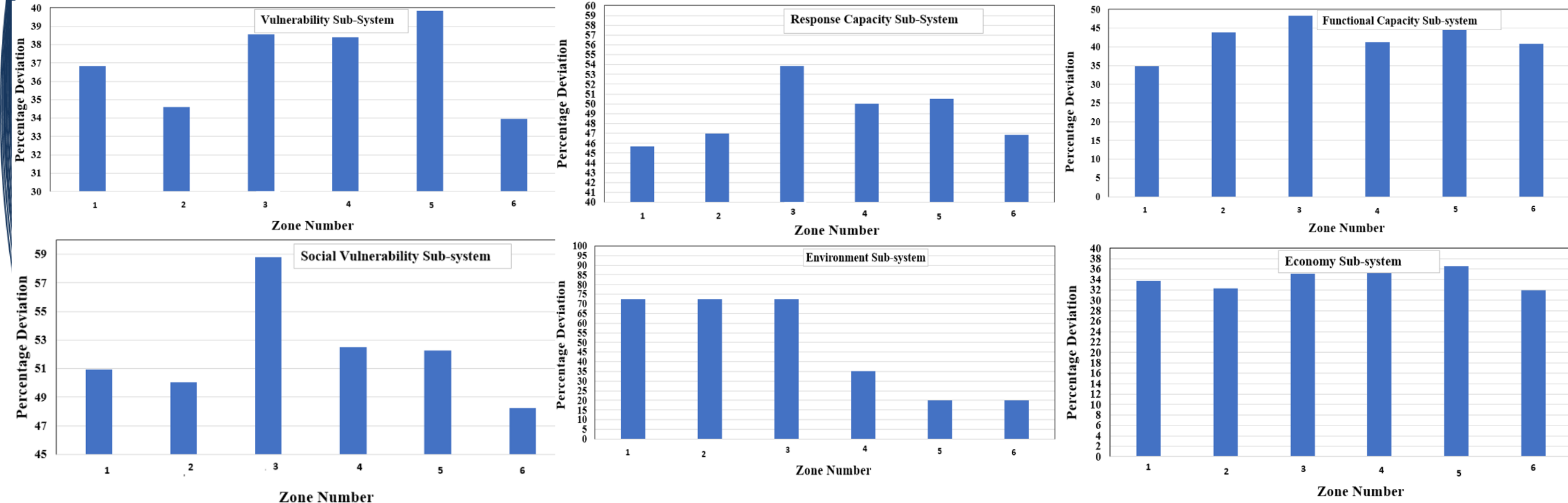
Step 4: Implementing Model in the Study Area

Estimation and Evaluation of Module Components (Level-5 Parameters) in the Study Area

Parameter	Criterion	Weight Reduction Coefficient				
		1	0.8	0.6	0.4	0.2
Bridges	Number of collapsed/extensively damaged bridges at each zone	0	1	2	3	3<
Tunnels	Number of extensively damaged tunnels at each zone	0	1	2	3	3<
Pavement	Ratio of the length of road segments in extensive or complete damage state, to the total length of roads at each zone using HAZUS fragility curves	0	5	5-10	10-15	15<
Retaining walls	Ratio of the length of road segments alongside the extensively or completely damaged retaining walls, to the total length of roads at each zone	0	<10	10-20%	20-30%	30-40
Gas networks	Number of rupture points in gas pipelines at each zone	0	3>	3-6	6-9	9-12
Water and wastewater networks	Number of rupture points in water and wastewater pipelines at each zone	0	3>	3-6	6-9	9-12
Preparedness of maintenance teams	Questionnaire-based survey	Very high	High	Moderate	Low	Very low
Preparedness of traffic control police	Questionnaire-based survey	Very high	High	Moderate	Low	Very low
Preparedness of emergency response teams	Questionnaire-based survey	Very high	High	Moderate	Low	Very low

Step 4: Implementing Model in the Study Area

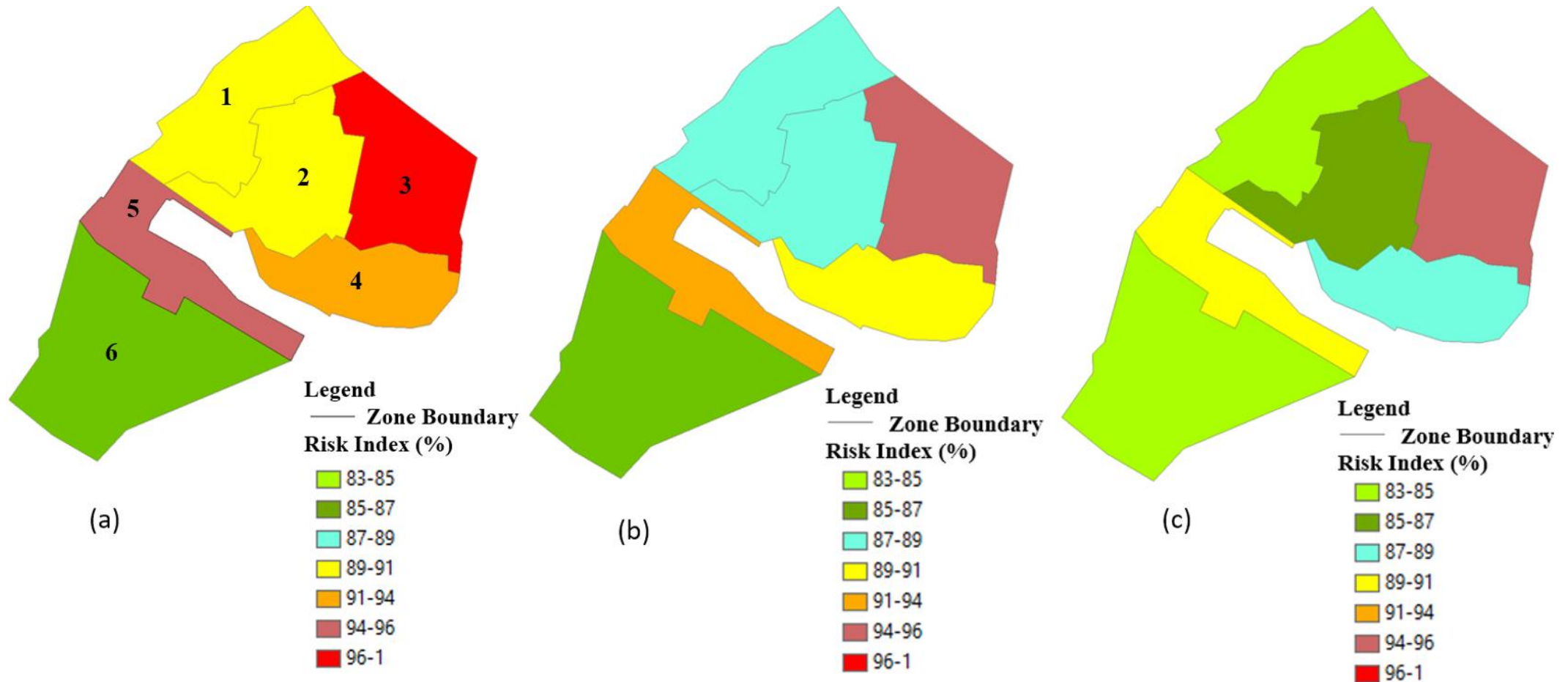
Estimation of risk subsystems (level-3 parameters)



Percentage change of each subsystem in each zone relative to the ideal condition

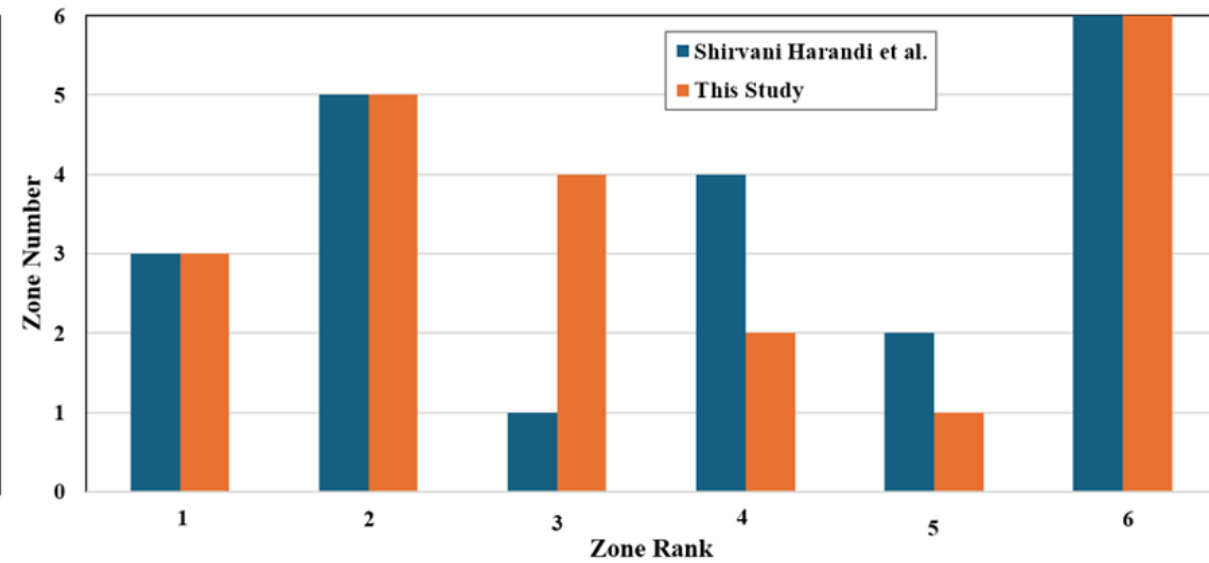
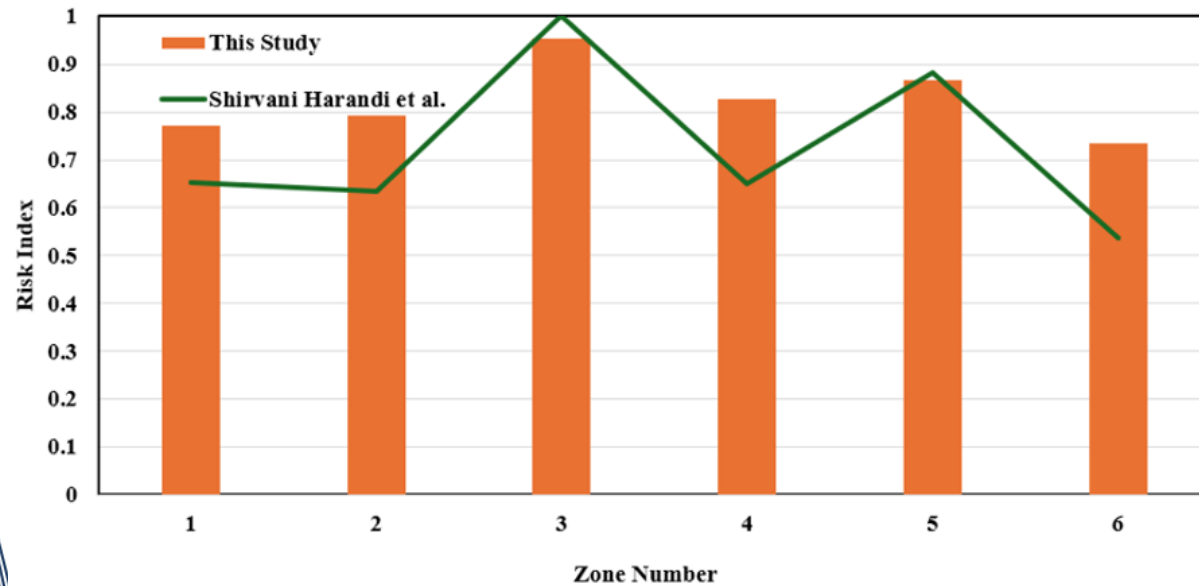
Step 4: Implementing Model in the Study Area

Estimation of risk in each zone



Zone-level Risk Index across District 4 of Qom under three earthquake scenarios: (a) 6:00 p.m. (peak traffic), (b) 12:00 p.m. (moderate traffic), and (c) 2:00 a.m. (low traffic).

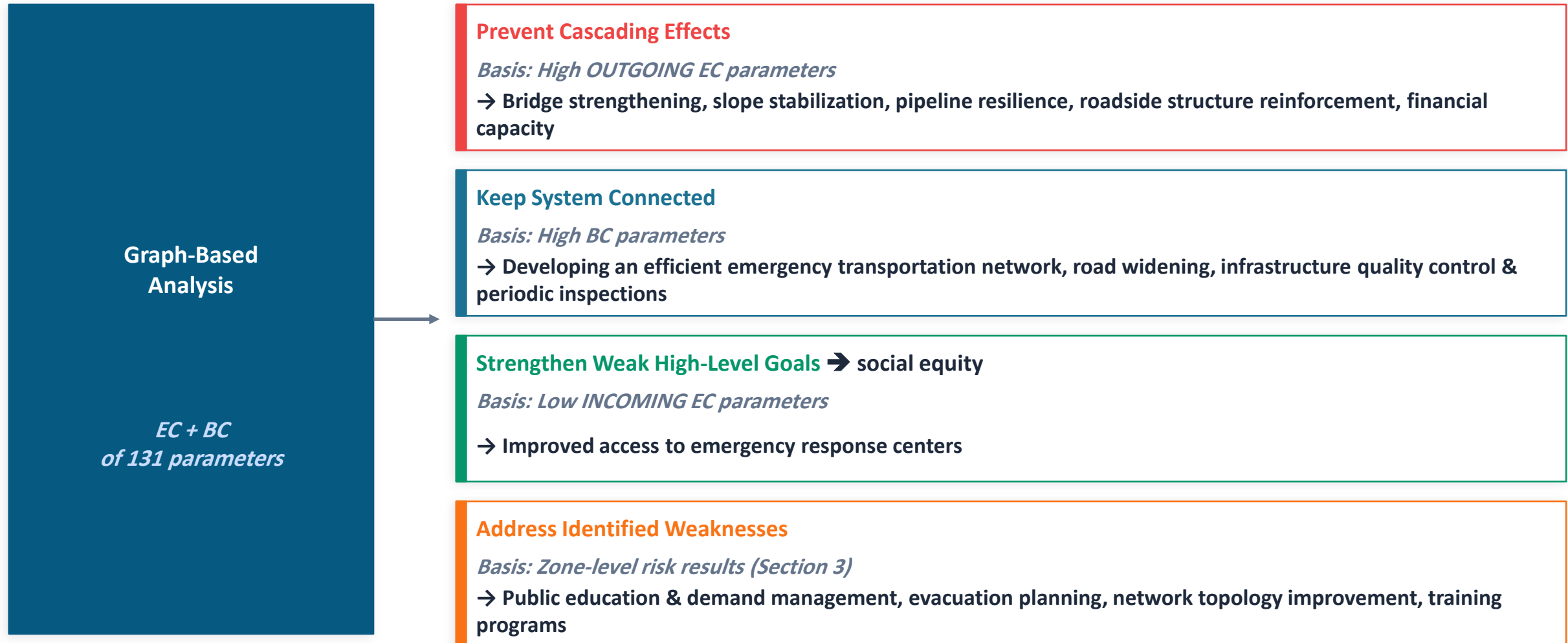
Step 5: Model Verification



Step 6: identifying and prioritizing mitigation interventions:

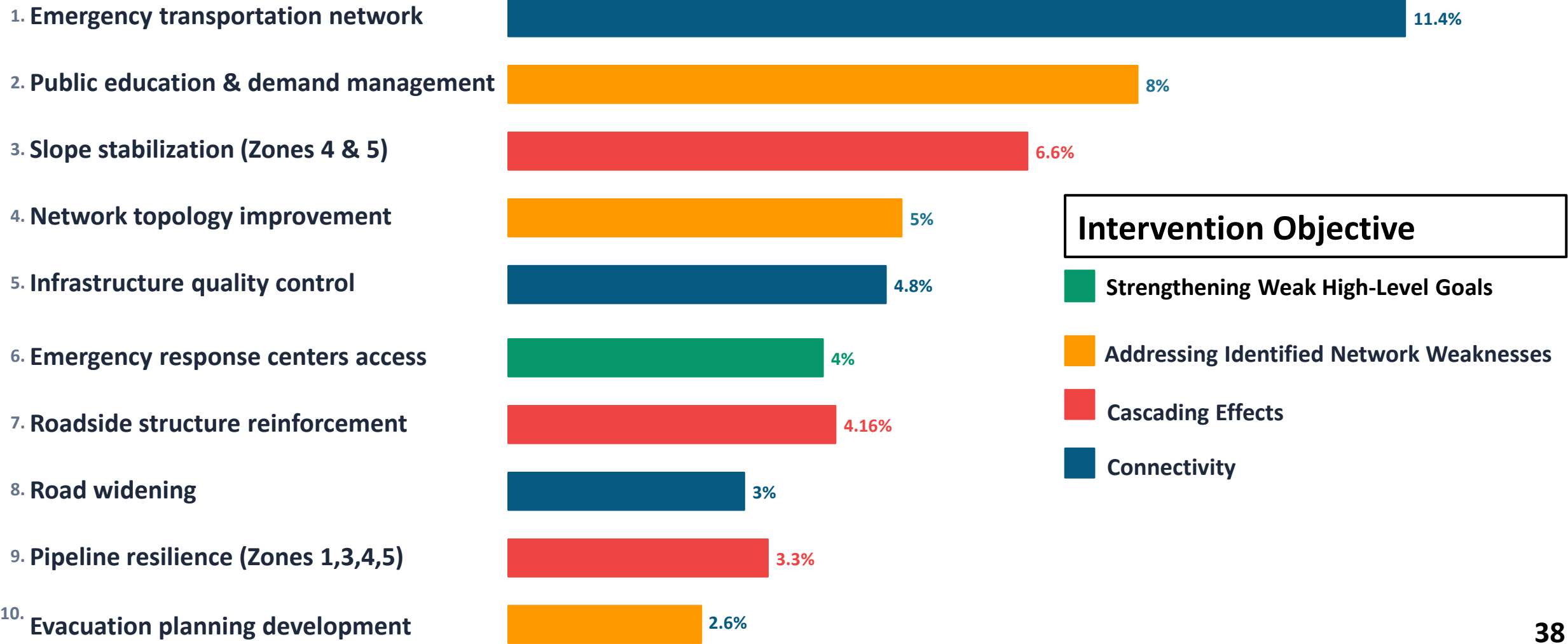
How Were Interventions Selected?

EC & BC analysis from companion study → four intervention objectives



Step 5: identifying and prioritizing mitigation interventions:

22 interventions ranked by average Risk Index reduction across study area



Key Conclusions

01

Traceable Risk Index

β -matrix formulation preserves cascading structure across 5 hierarchical levels → zone-level RI is directly traceable to Level 5 parameter conditions.

02

Dominant Subsystems

Infrastructure vulnerability (55%) and response capacity (48%) dominate seismic risk. Emergency transportation network absence = largest single intervention impact (11.4%).

03

EC/BC → Intervention Basis

Outgoing EC → cascading interventions.
High BC → connectivity.
Low incoming EC → weak high-level goals. Zone results → targeted weaknesses.

04

Decision-Support Tool

22 prioritized interventions across 4 graph-grounded objectives provide a reproducible, model-grounded basis for seismic risk reduction.

Thanks for your attention!

Results of limited model (by removing low centrality parameters))

