Urban-Net: *A System to Understand and Analyze Critical Infrastructure Networks for Emergency Management*

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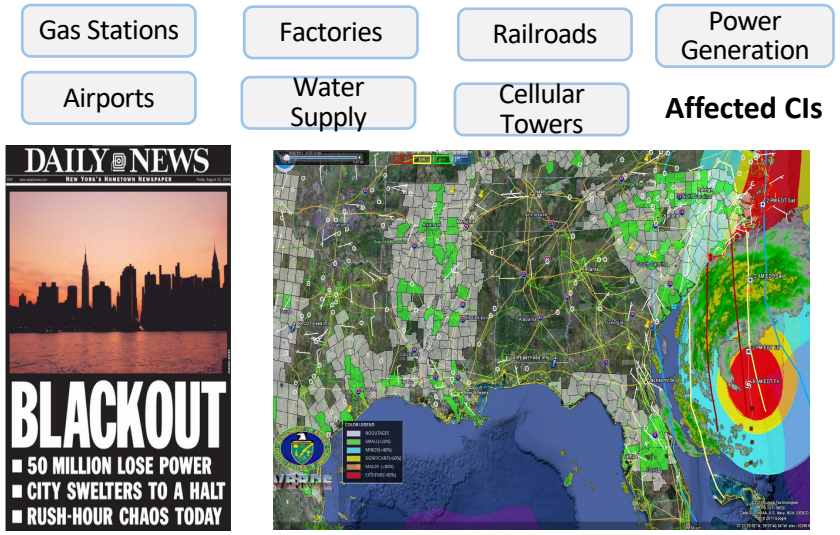
Background

- Critical infrastructure Systems (CIS) are crucial for sustaining day-to-day commodity flows vital to national security (e.g., Energy, water, transportation)

- An extreme weather event or a human-caused incident can trigger widespread cascading failures



Northeast Blackout in US (2003)
Puerto Rico Blackout in US(2016)

Hurricane Sandy (2012)

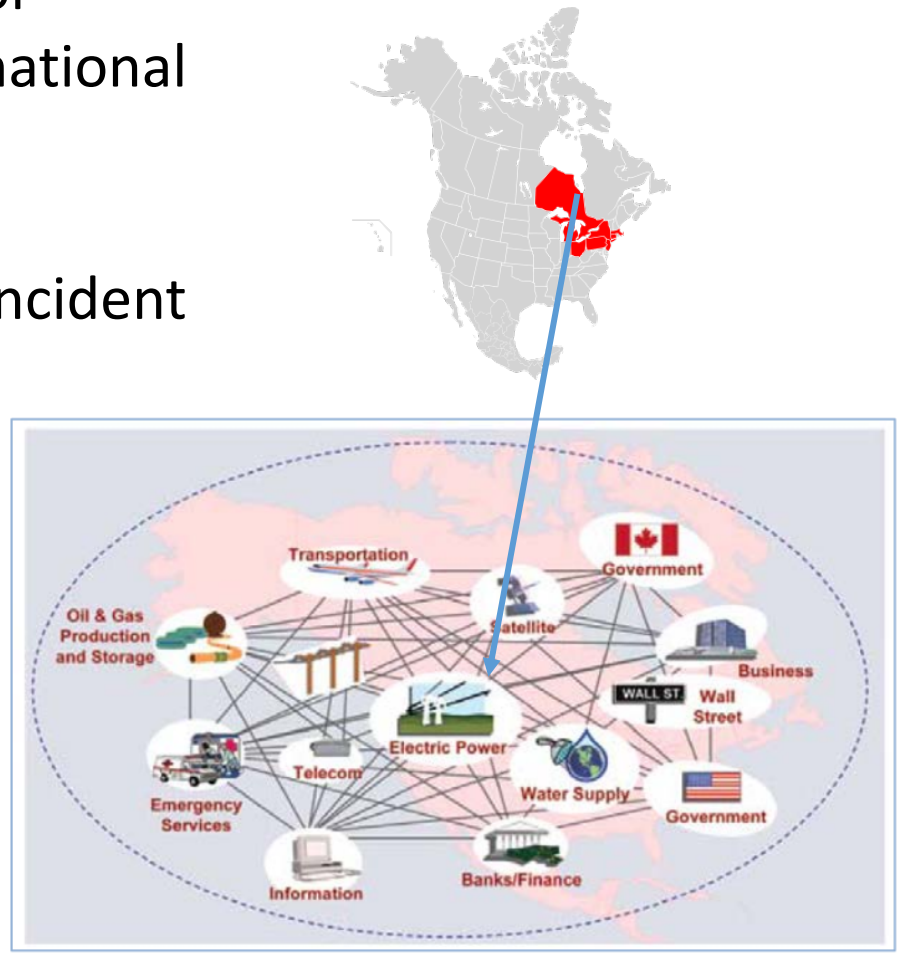
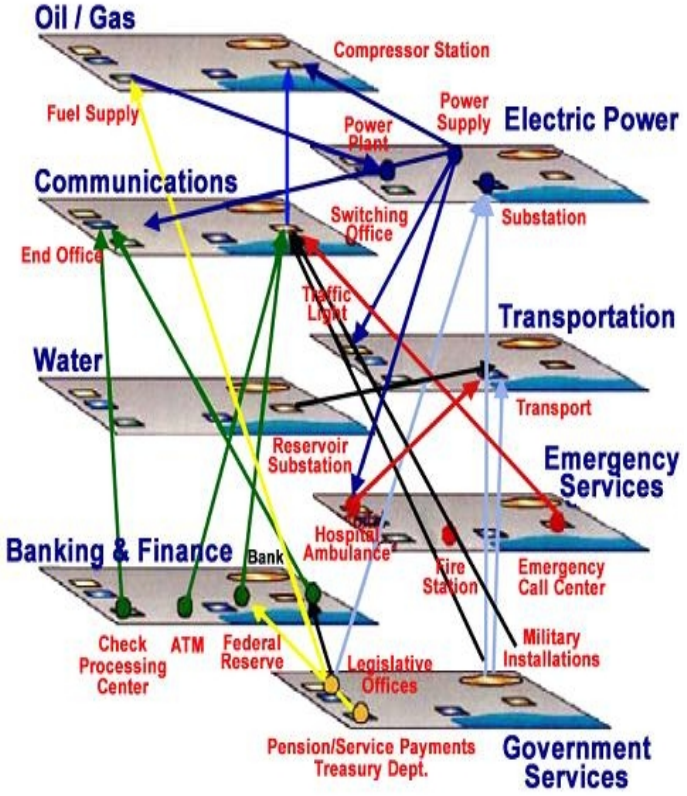


Fig: 2003 NorthEast Balckout cascading effect

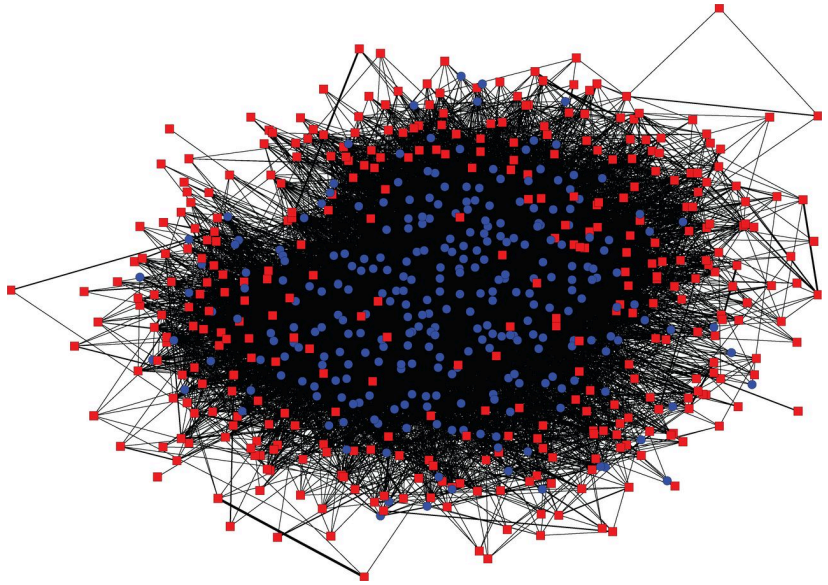
Motivation

- CIS are mutually interconnected, interdependent in complex ways
- Several layers of multidimensional data
- CIS Interdependencies can act as risk multipliers



Our Idea

View CIS as large heterogeneous networks with **nodes** representing *different CIS components* and **links** representing the *physical and relational connections* among them

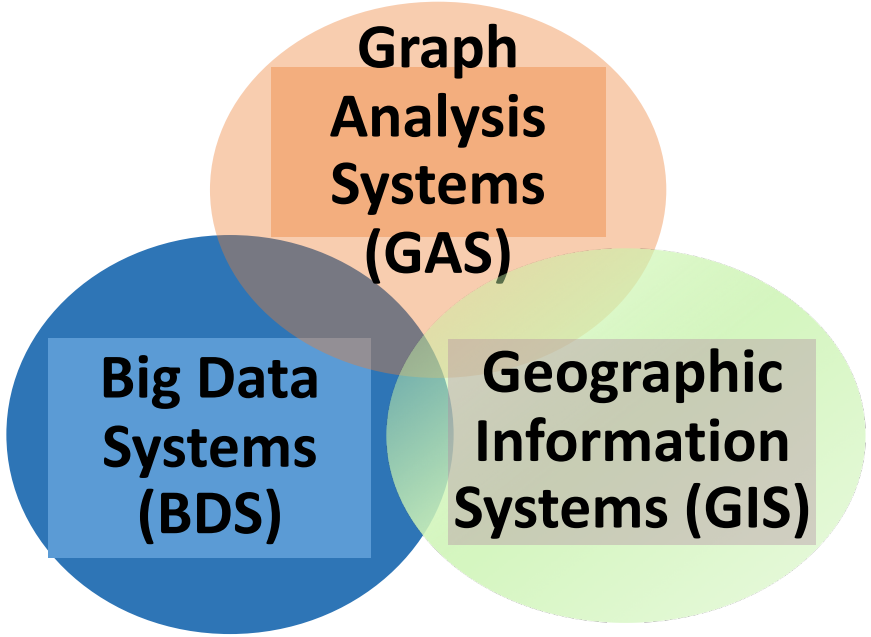


WHY?

- ✓ More general: can be applied for different systems
- ✓ Require less domain knowledge
- → Not as high fidelity, but great for quick understanding and decisions
- → Serve as input to more high fidelity frameworks

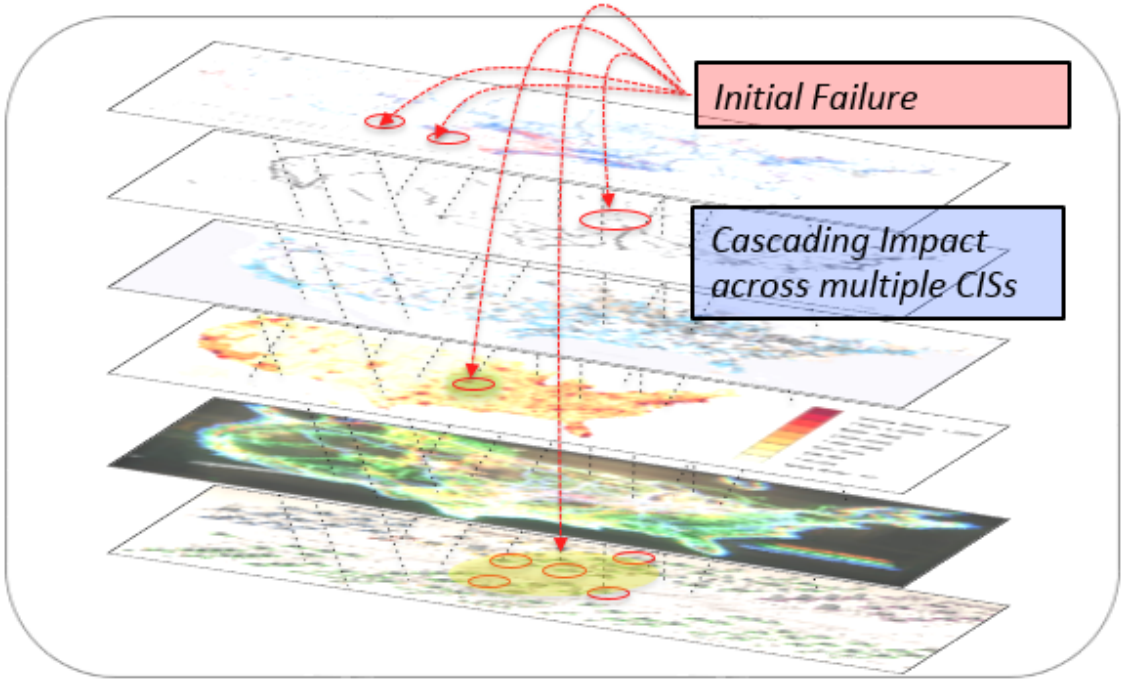
Challenges

- **Convert geographic data into graph**: need to handle millions of nodes and edges
- **Components have recovery/failures**: network needs to be flexible to add/remove a component
- **Effect and conditions of failures vary**: need analysis and tractable simulation with dynamically change of inputs based on topology and temporal dependencies



Urban-Net Tool

A **network based interactive visualization** and automated **decision-support** tool to model interdependency and failure dynamics over CIS.

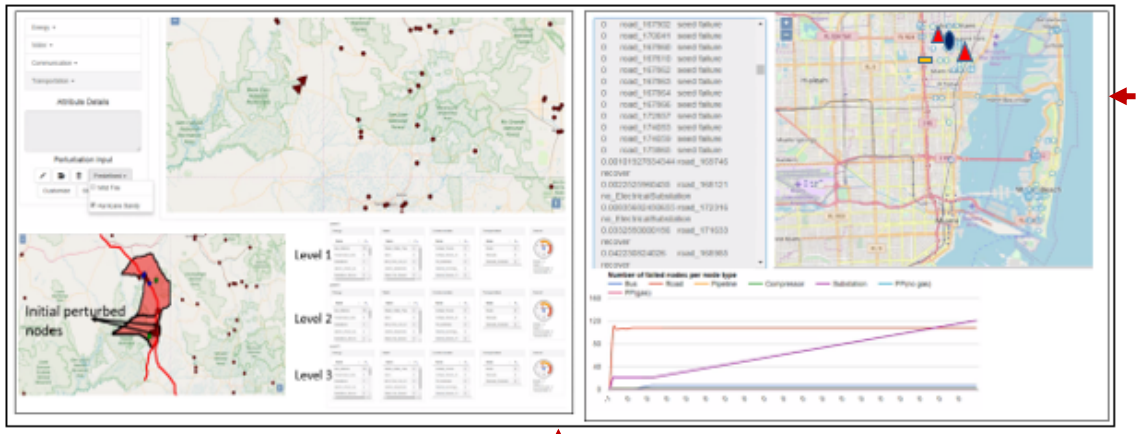


Core Capabilities

- ✓ Visualizing complex CIS interdependencies
- ✓ Identifying vulnerable components in CIS
- ✓ Predicting potential propagating impacts under certain scenarios

Architecture/Workflow

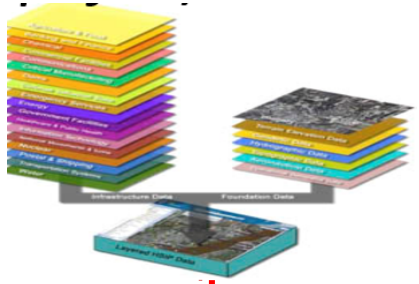
Situation Awareness Interface

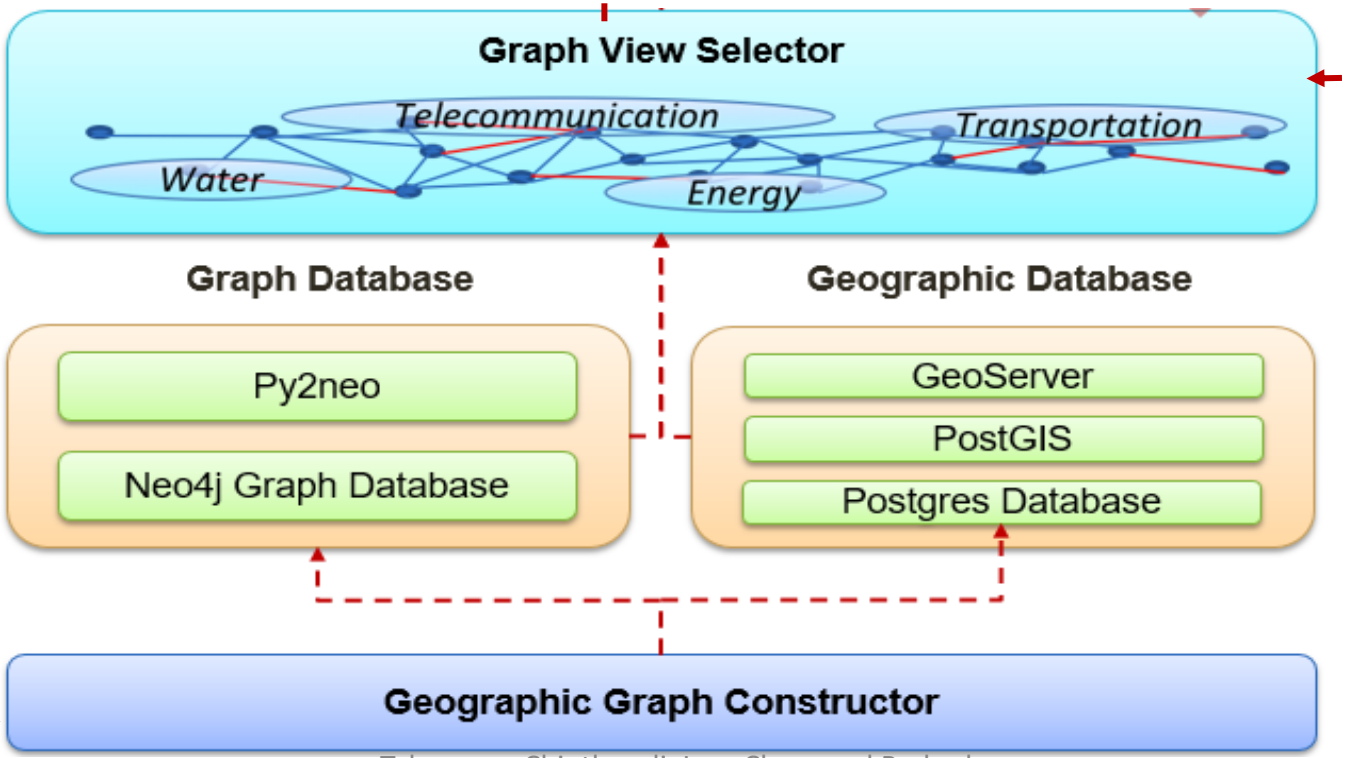


Domain Expert

No of Nodes	~82M
No of edges	~83M
No of node types	32
No of edge types	31

HomeLand Security Infrastructure Program (HSIP) Gold Dataset





Analytic modules: Topology-based

Identify potentially affected entities across different CIS when one/more perturbation entities are selected from a CIS network

To understand

✓ How efficient is the CIS network as a whole?

✓ What are the most important nodes/edges in the network whose malfunctioning cause largest impact?

✓ What are the consequences of a given perturbation event (e.g., hurricane, earthquake)?

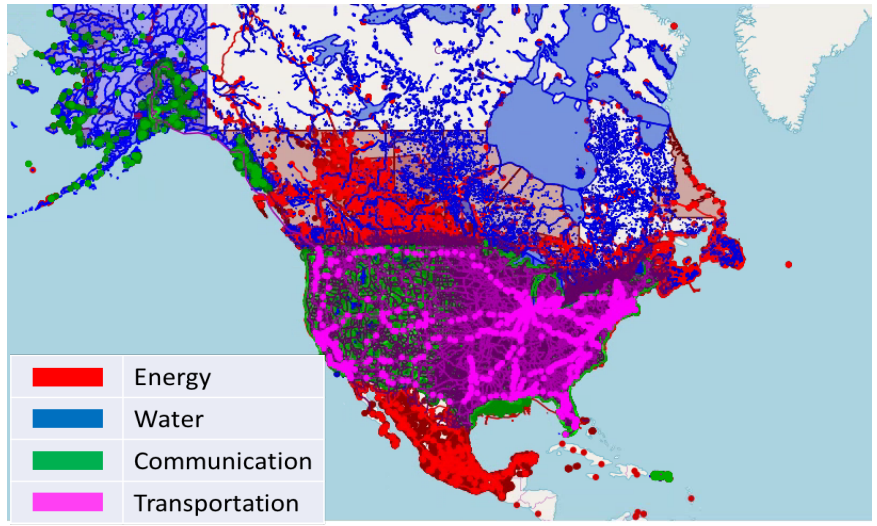
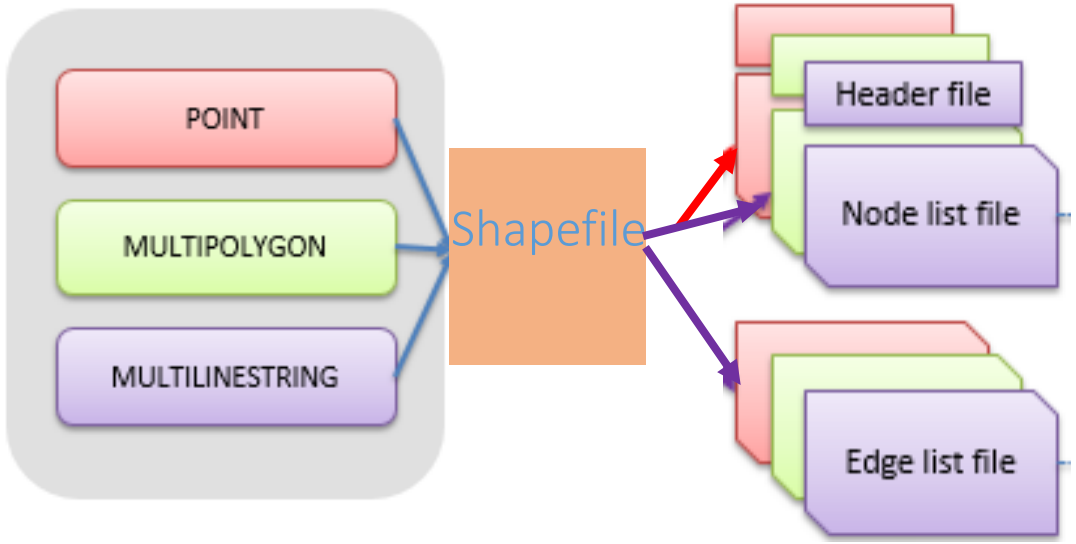


Fig: The whole CIS network of US

Difficult to understand anything from this visualization

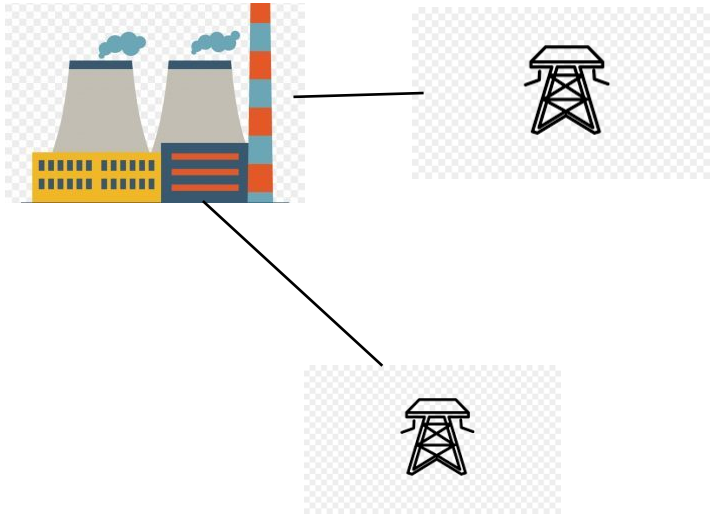
Topology-based module: Steps

Converting shapefile to graph



Neo4j Graph database

How to link nodes of different CIS in network?

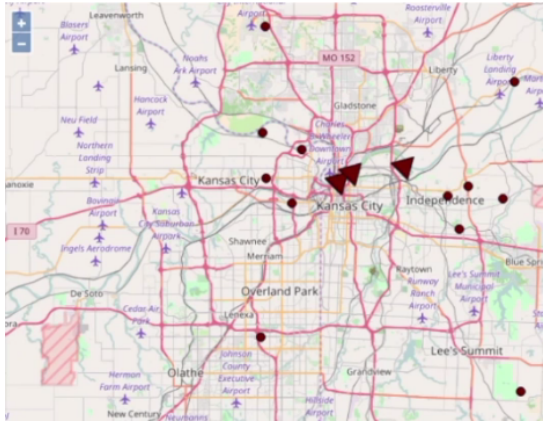


Geographically nearest substation which are located in k-edge distance

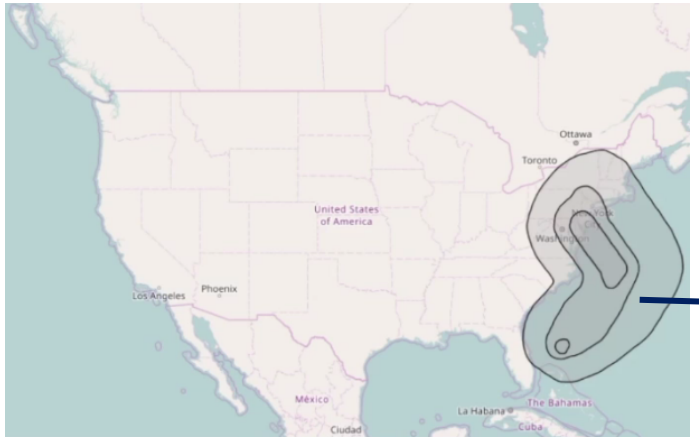
Topology-based module: Steps

Selecting initial failures (perturbation)

1. Random selection



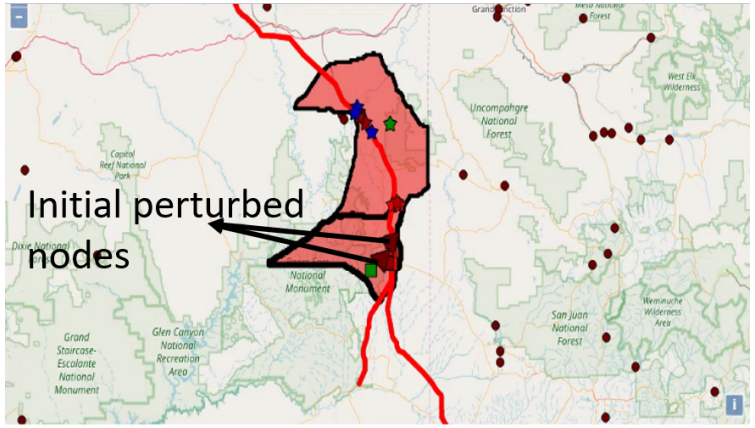
2. Case study region-based selection



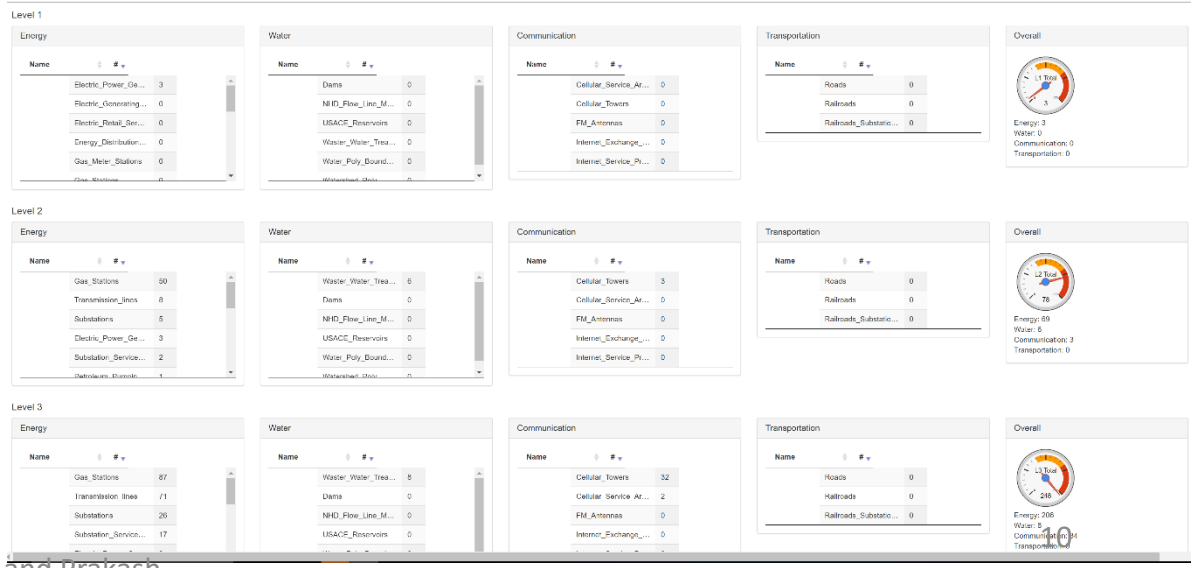
Hurricane Sandy region

Affected entities in 2k (15) edge distance

Map View



Three level detail view

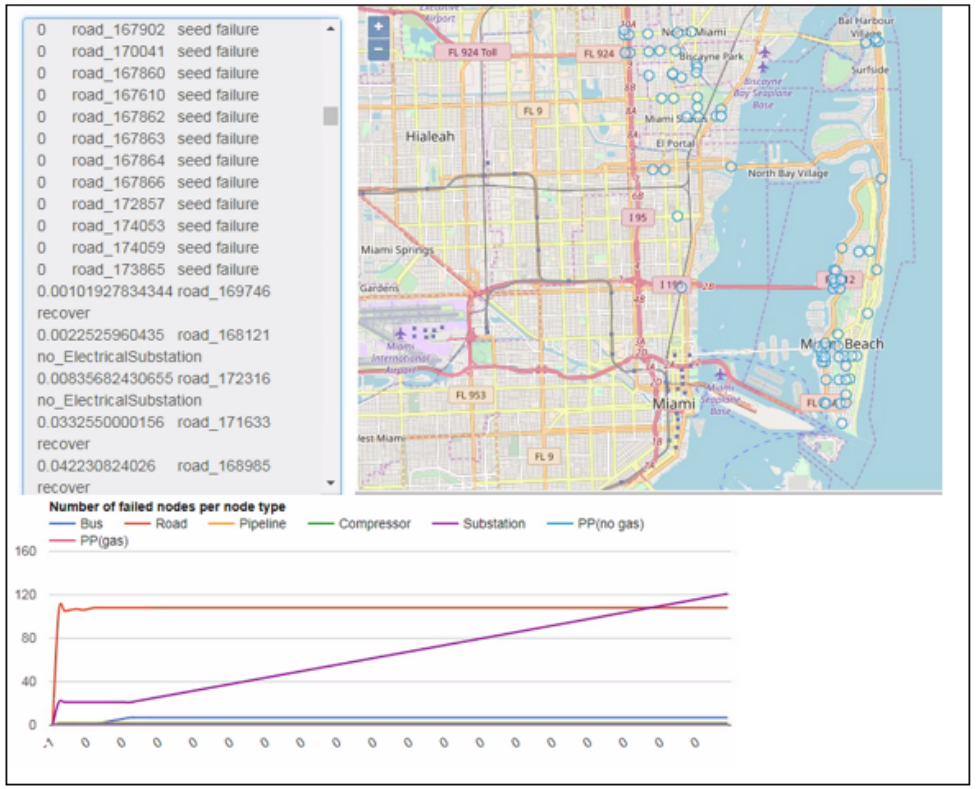


Analytic modules: Simulation-based

Very important to understand the impacts of failure cascade based on temporal delay (e.g., recovery period)

To understand

- ✓ Real-time consequences of CIS grid layers
- ✓ Temporal aspects along with physical interdependencies
- ✓ Identify critical facilities that may largely impact the entire CIS



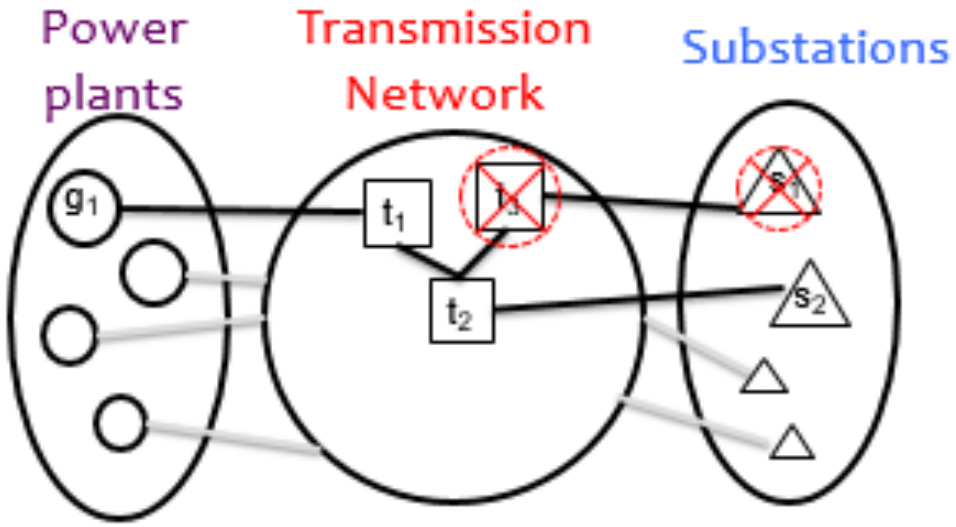
Snap-shot of simulation-based module

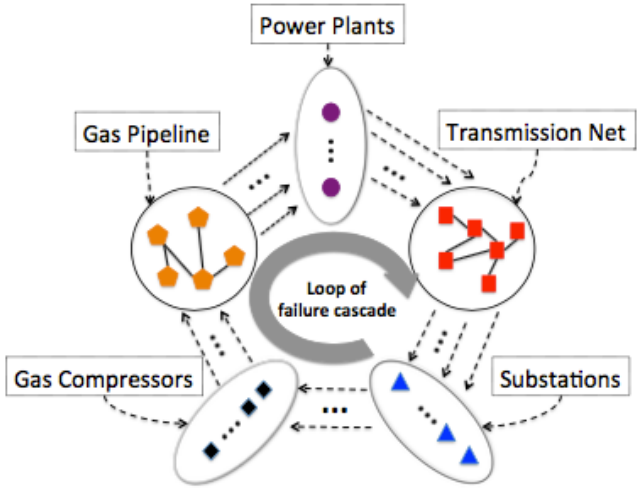
Simulation-based module: Steps

Model failure cascade (F-CAS) on heterogeneous CIS energy network

❑ Proposed F-CAS Model:

- If a substation has **no path** in the trans. network to any power plant, it fails.

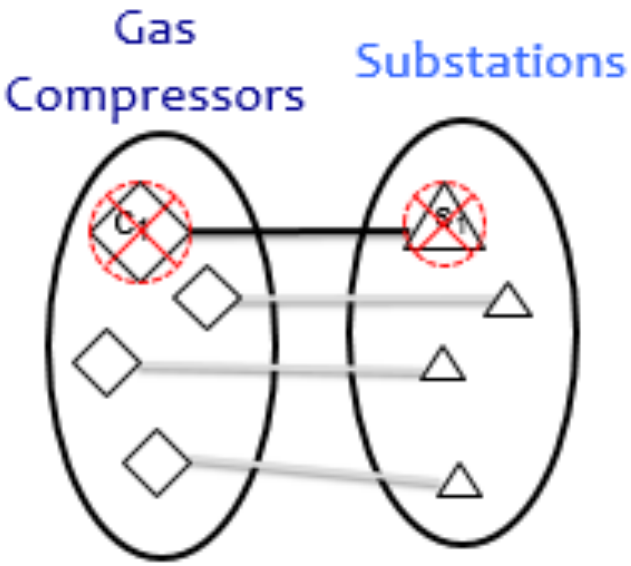


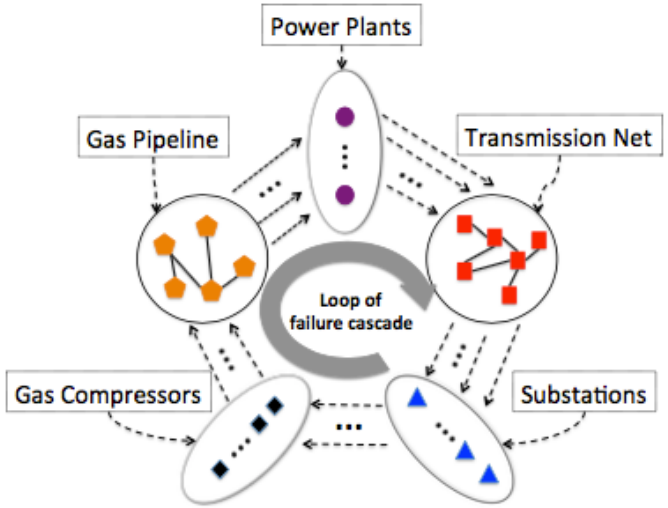


Simulation-based module: Steps

❑ Proposed F-CAS Model:

- If a substation has no path in the trans. network to any power plant, it fails
- If a natural gas compressor's associated substation fails, it fails

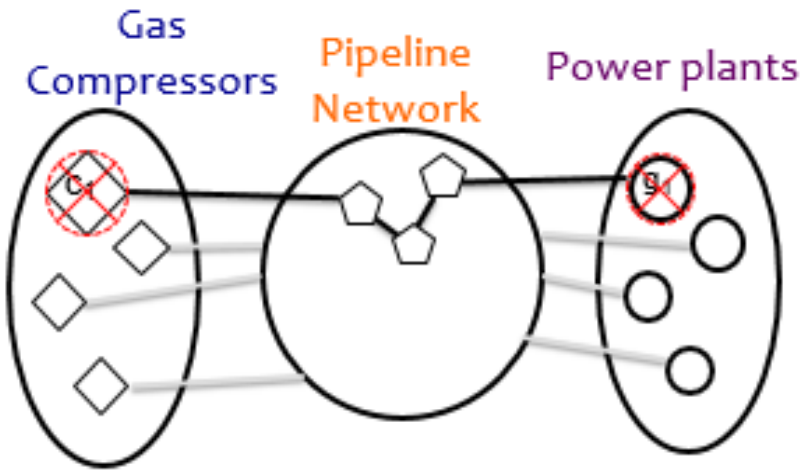


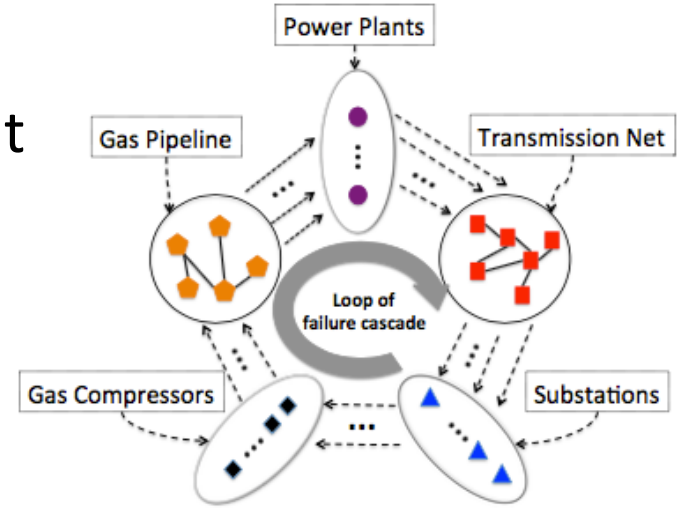


Simulation-based module: Steps

❑ Proposed F-CAS Model:

- If a substation has no path in the trans. network to any power plant, it fails.
- If a natural gas compressor's associated substation fails, it fails.
- If a power plant's reachable natural gas compressor fails, it fails





Simulation-based module: Steps

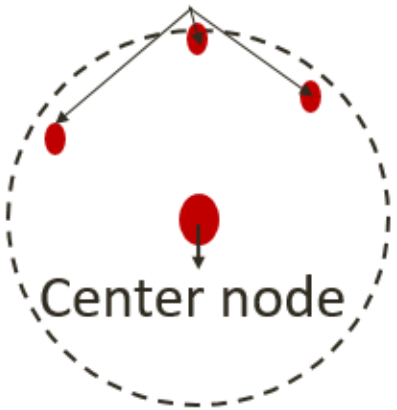
Selecting Initial failures (a what-if scenario)

By State

Randomly sample nodes from the selected state

By Point

All nodes in 10km radius



Every type of node has four user-control parameters

α: recovery time

β: time to loose control before turning into inactive node

L: load

C : capacity

Simulation-based module: Steps

Iteration (At each cascade):

- ✓ Identify and enlist the failed nodes due to current cascade whose L>C
- ✓ Schedule recovery time for each failed node
- ✓ Distribute load of failed nodes to the connected components

End simulation:

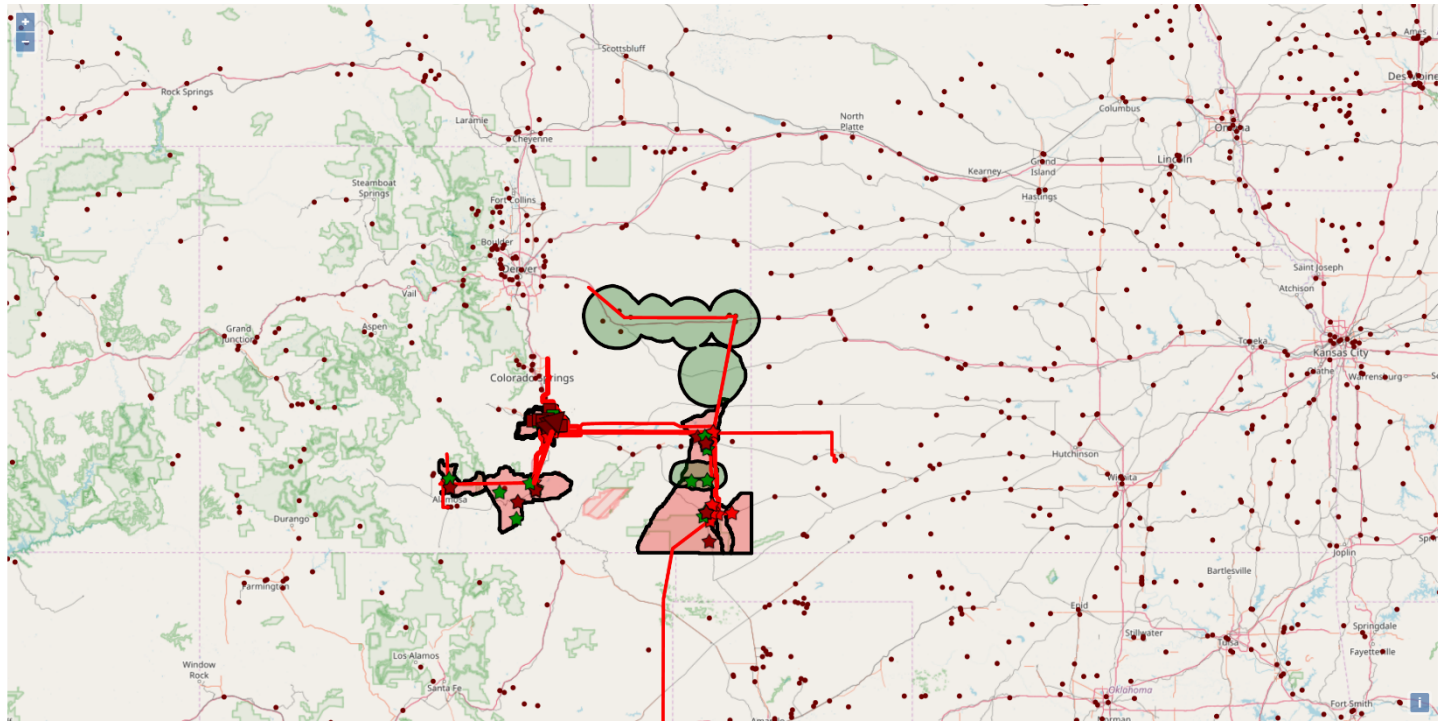
When all node becomes active

Or

Recovery time of all failed nodes reaches its maximum

Scenarios: Topology-based

Initial selection: Two electric power-plant generator to fail

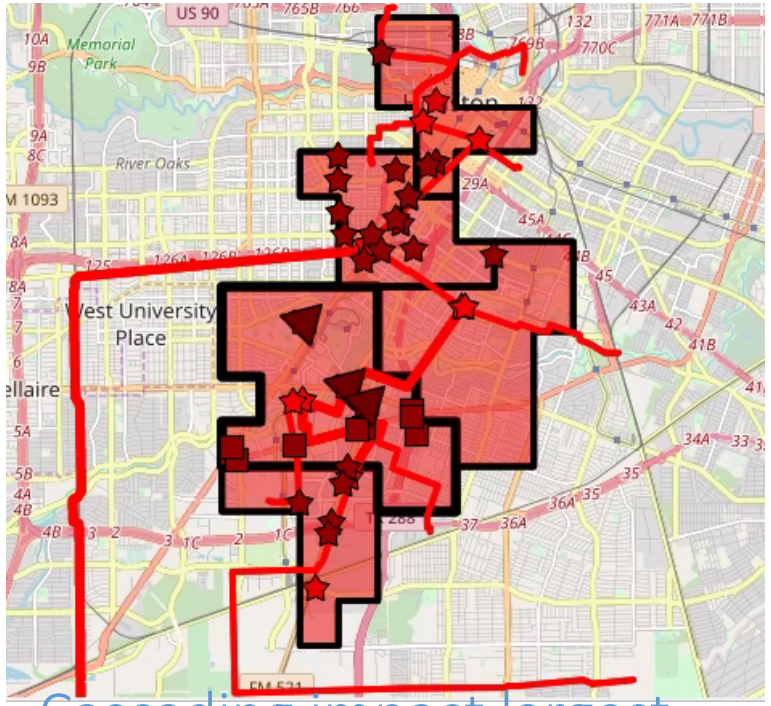


Consequence:

- ✓ Failures affect components in multiple layers
- ✓ Cascading impact components which are located geographically far

Scenarios: Topology-based

Initial selection: Three electric power-plant generator in Southern Houston (the most affected area during hurricane Harvey)



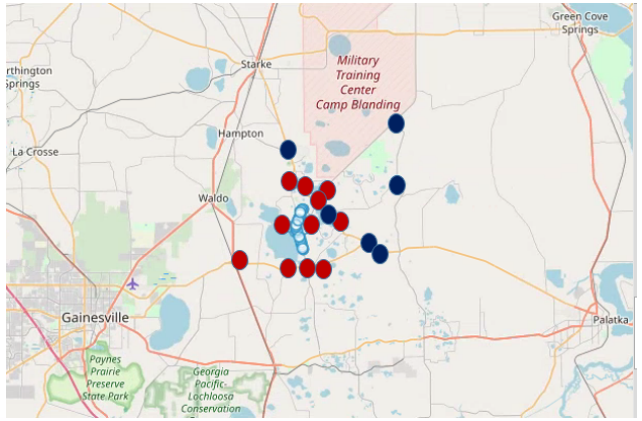
Cascading impact largest components (substations)

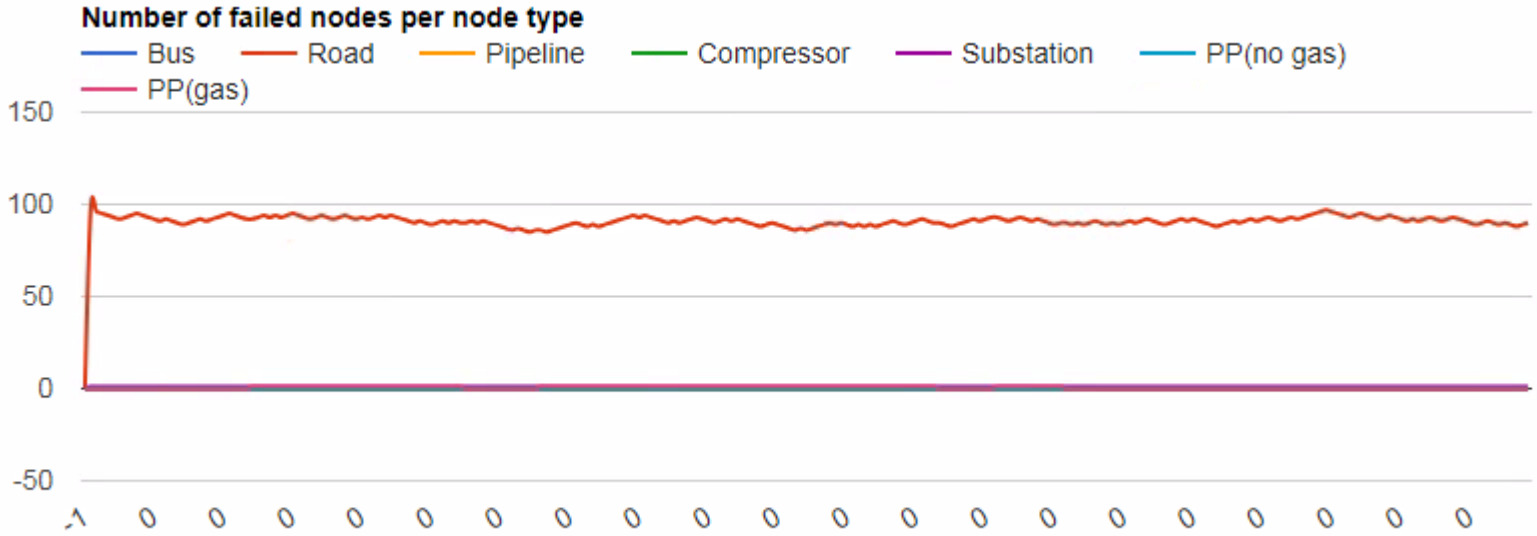
Consequence

- ✓ Identifies which subset can affect largest CIS components
- ✓ Affects 68 energy nodes within this smaller area

Scenarios: Simulation-based

Initial selection: State Florida (the most affected state during Hurricane Irma)





Consequence:

- ✓ Heavily damaged road networks at the end of hurricane

Future Plan

Explore our avenue of research for

✓Cyber

✓Water

✓Transportation

Importance of Urban-Net

- ✓ For emergency planning by DOE for their emergency support framework
- ✓ A national scale tool, can simulate any scenario at any place
- ✓ Can show the components having largest impacts along with the cause of these impacts
- ✓ Licensed by VT and ORNL, for use at utilities

References

1. Tabassum, Anika, et al. "Data Mining Critical Infrastructure Systems: Models and Tools." IEEE *Intelligent Informatics* Bulletin . 2018

2. Chen, Liangzhe, et al. "Hotspots: Failure cascades on heterogeneous critical infrastructure networks." Proceedings of the CIKM. 2017

3. Lee, Sangkeun, et al. "URBAN-NET: A network-based infrastructure monitoring and analysis system for emergency management and public safety." *IEEE International Conference on Big Data Workshop*. 2016.

Thank you

Questions??