

Vulnerability of Urban Road Systems

A Network Analysis of the Baltimore Bridge Collapse

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Background

The Event



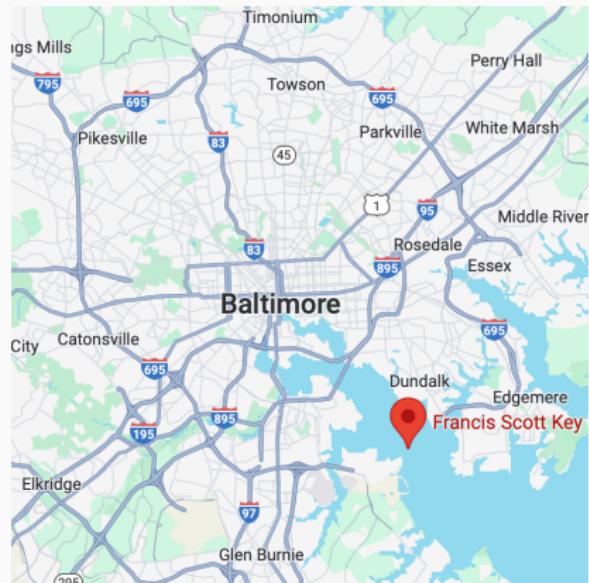
On March 26, 2024, the *Dali* struck and collapsed the Francis Scott Key Bridge

Key Bridge

The Francis Scott Key Bridge is part of I-695, or Baltimore Beltway

It's an important part of the Baltimore Road System

- 30,000 cars travel across it every day
- Spans the entire port of Baltimore (1.6 Miles)



Screenshot from Google Maps

Questions

How did the bridge collapse affect the road network as whole?

Where are these effects concentrated?

Empirical Strategy

The Network (1/3)

Create a network using intersections as nodes and road segments as edges

The “Primal Approach” (Porta, Crucitti, and Latora 2006)

Compare this network with and without the bridge edges

The Network (2/3)

We get our network from OSMnx, a Python library that uses Open Street Maps to create a directed multigraph for any road system in the world (Boeing 2017)

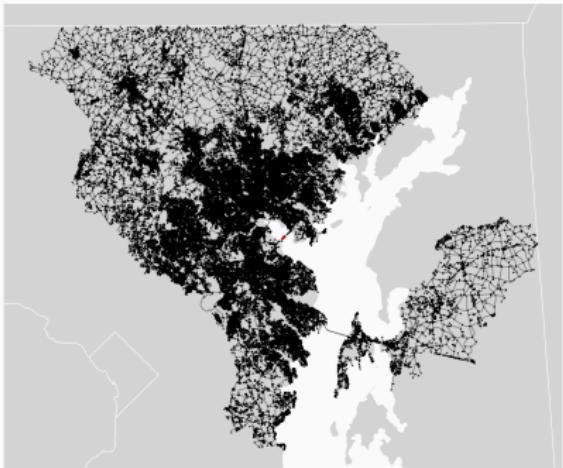
7 counties in the BMA: Anne Arundel, Baltimore City, Baltimore County, Carroll, Harford, Howard, and Queen Anne's

Filter out 272 nodes that aren't a part of the largest strongly connected component

End up with a network with

- 91,300 nodes (intersections)
- 218,842 edges (road segments)
- 4 collapsed road segments

The Network (3/3)



Total BMA Network



Zoomed In to Key Bridge

Key Bridge highlighted in red.

Method

Analyze global network effects using average shortest path length

Analyze local effects using Multiple Centrality Analysis (MCA)

(Porta, Crucitti, and Latora 2006; Porta and Latora 2007; Barthelemy and Flammini 2009; Jayaweera, Perera, and Munasinghe 2017)

- Eigenvector Centrality: High traffic “important” areas
- Betweenness Centrality: Important routes
- Closeness Centrality: Areas with high land use, can have issues on a bounded network
- Straightness Centrality: Important routes and land use

Analyze the impacted paths for even more localized effects

Straightness Centrality

Straightness Centrality is a measure specific to spatial networks that measures how directly you can travel to other nodes

$$C_i^S = \frac{1}{n - 1} \sum_{j \in N, j \neq i} \frac{d_{i,j}^{\text{Eucl}}}{d_{i,j}}$$

Results

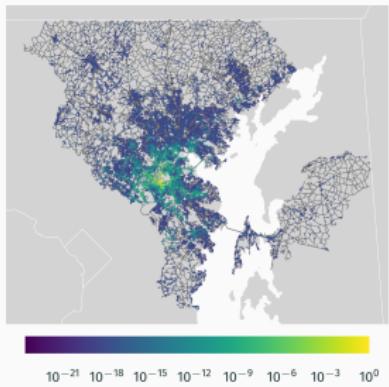
Average Shortest Path

The average shortest path was only marginally affected

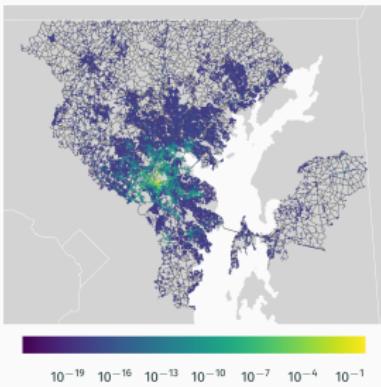
Before Collapse	After Collapse	Difference	% Difference
26.3	26.4	0.09	0.003

Length of the average shortest path in the BMA road network (Miles)

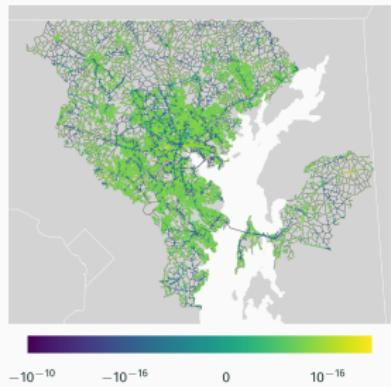
MCA: Eigenvector Centrality



Eigenvector Centrality
before the collapse

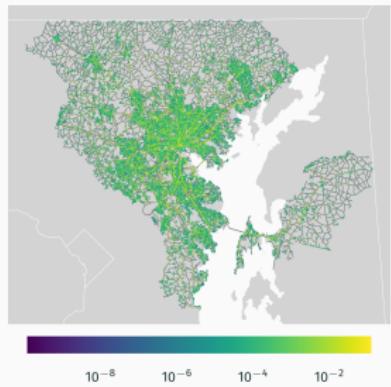


Eigenvector Centrality after
the collapse

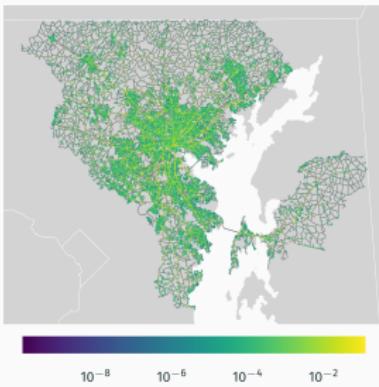


Change in Eigenvector
Centrality

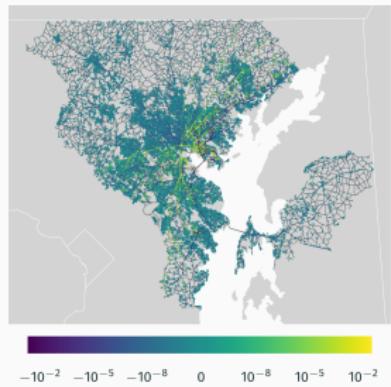
MCA: Betweenness Centrality



Betweenness Centrality
before the collapse

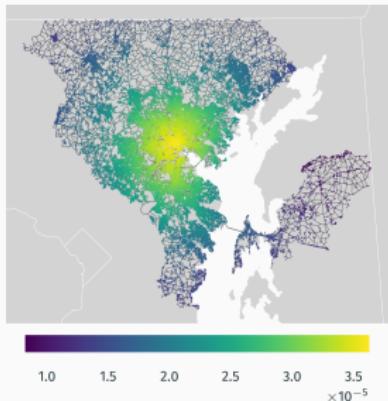


Betweenness Centrality
after the collapse

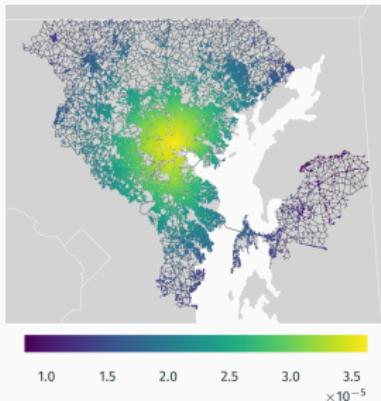


Change in Betweenness
Centrality

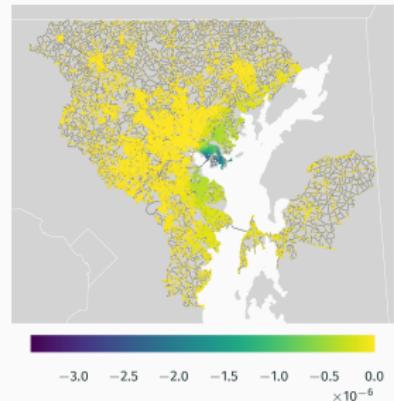
MCA: Closeness Centrality



Closeness Centrality before
the collapse

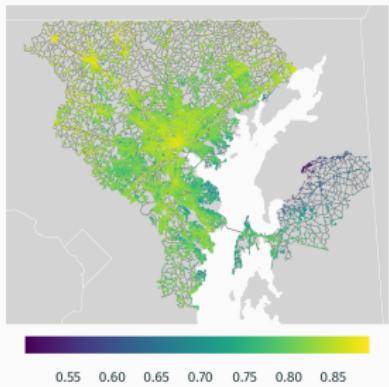


Closeness Centrality after
the collapse

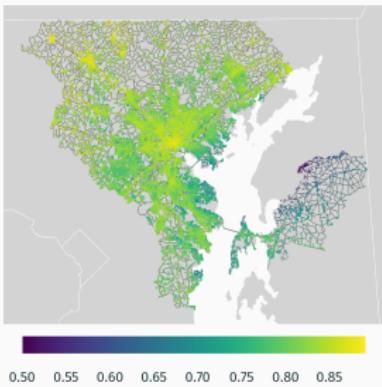


Change in Closeness
Centrality

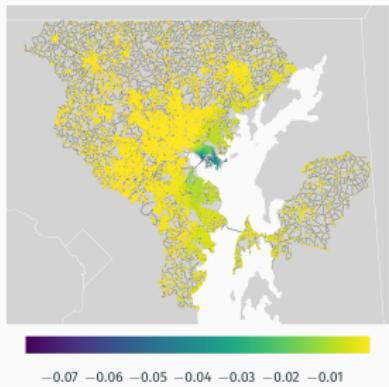
MCA: Straightness Centrality



Straightness Centrality
before the collapse



Straightness Centrality after
the collapse



Change in Straightness
Centrality

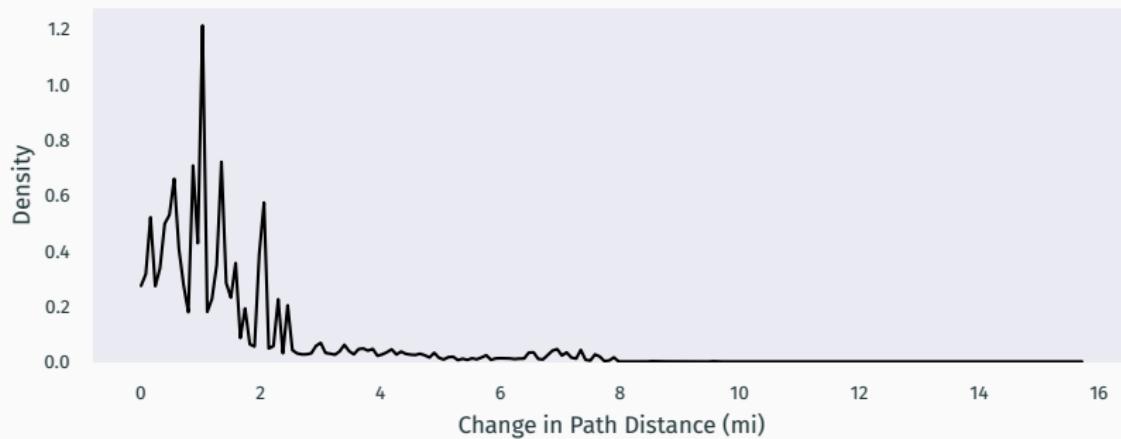
Impacted Shortest Paths (1/3)

475 million paths were impacted (0.57% of total paths)

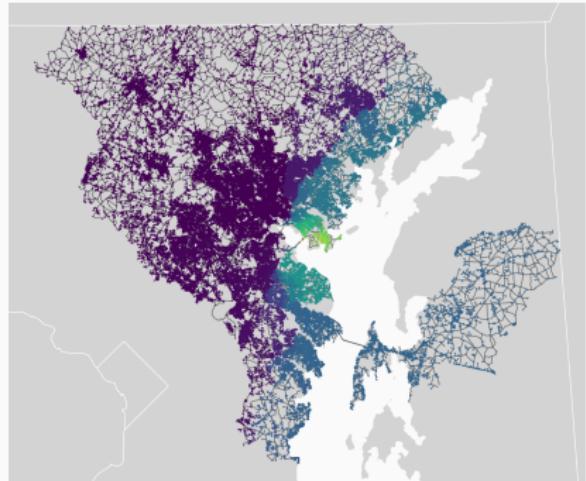
Count	Mean	St. Dev.	Min	25%	Median	75%	Max
4.750×10^8	1.525	1.514	1.864×10^{-6}	0.559	1.049	2.018	15.716

Unit: Miles

Impacted Shortest Paths (2/3)

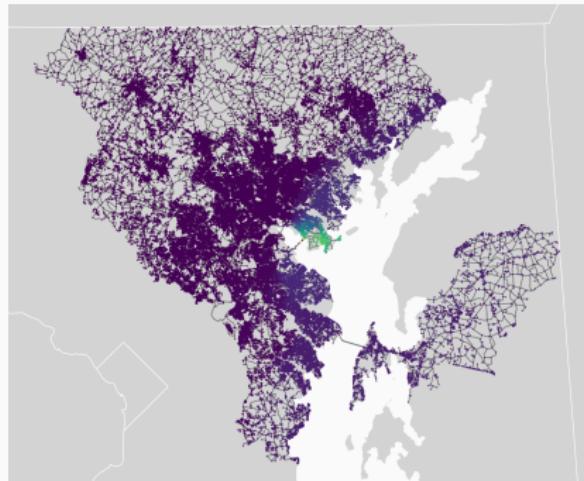


Impacted Shortest Paths (3/3)



Number of Impacted Paths Starting at

Node



Total Distance Added in Paths Starting at

Node

Conclusion

Conclusions

The effects of the bridge collapse were insignificant at a global level, but are significant for individual nodes

- Nodes near the bridge: harder to travel through the network (straightness, closeness, paths from node)
- Webs of nodes through the whole network: different levels of traffic importance (eigenvector, betweenness)

Limitations

There are many limitations, including

- The network boundary and size is arbitrary
- The metrics analyzed are limited and don't include clustering coefficient, largest connected component size, or community deviations, which are standard in attack literature (Xeumei and Xiaochen 2010)

Farther Work

Future work could

- Analyze the types of nodes affected
- Look at usage (use average annual daily traffic numbers)

Questions?

References i

- Barthelemy, Marc, and Alessandro Flammini. 2009. "Co-evolution of density and topology in a simple model of city formation." *Networks and Spatial Economics* 9:401–425.
- Boeing, Geoff. 2017. "OSMnx: New Methods for Acquiring, Constructing, Analyzing, and Visualizing Complex Street Networks." *Computers, Environment and Urban Systems* 65:126–139.
- Jayaweera, I.M.L.N., K.K.K.R. Perera, and J. Munasinghe. 2017. "Centrality Measures to Identify Traffic Congestion on Road Networks: A Case Study of Sri Lanka." *IOSR Journal of Mathematics* 13 (2): 13–19.

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- Porta, Sergio, Paolo Crucitti, and Vito Latora. 2006. "The network analysis of urban streets: a primal approach." *Environment and Planning B: Planning and Design* 22:705–725.
- Porta, Sergio, and Vito Latora. 2007. "Multiple centrality assessment: mapping centrality in networks of urban spaces." In *Urban Sustainability through Environmental Design*, edited by Kevin Thwaites, Sergio Porta, Ombretta Romice, and Mark Greaves, 101–105.

Xeumei, Zhou, and Wu Xiaochen. 2010. "The Study of Reliability About the Internal Network of Shanghai South Railway Station Based on the Robustness of Complex Networks." *2010 International Conference on Optoelectronics and Image Processing.*