Vulnerability of Urban Road Systems

A Network Analysis of the Baltimore Bridge Collapse

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Background

The Event

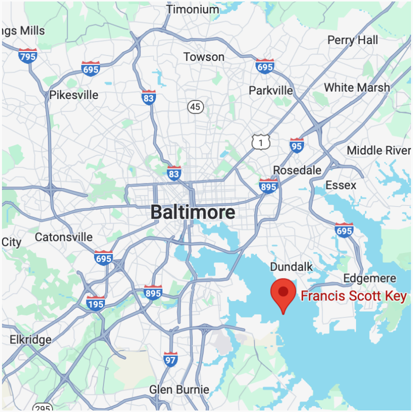
On March 26, 2024, the *Dali* struck and collapsed the Francis Scott Key Bridge

Key Bridge

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

It's an important part of the Balitmore 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)

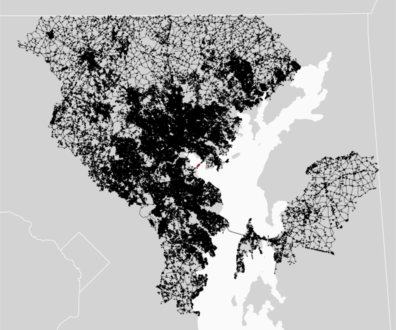
7 counties in the BMA: Anne Arundel, Baltimore City, Baltimore County, Carroll, Harford, Howard, and Queen Anne’s County

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 (Xeumei and Xiaochen 2010; Kaub et al. 2024)

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

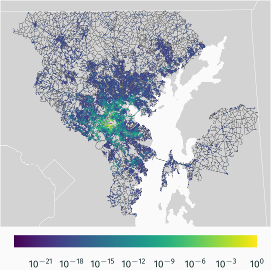
Average Shortest Path

The average shortest path was only marginally affected

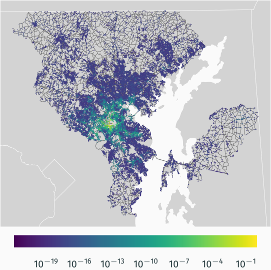
Before Collapse	After Collapse	Difference	% Difference
26.3	26.4	0.09	0.003

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

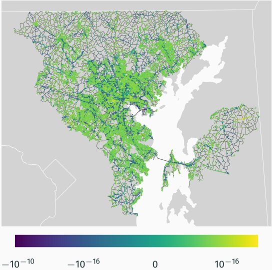
MCA: Eigenvector Centrality



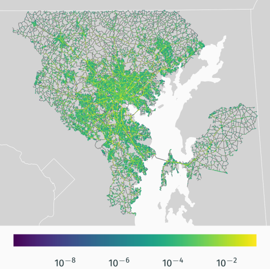
Eigenvector Centrality before the collapse



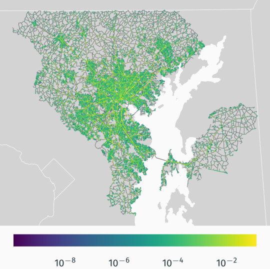
Eigenvector Centrality after the collapse



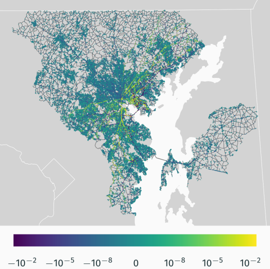
Change in Eigenvector Centrality



Betweenness Centrality before the collapse

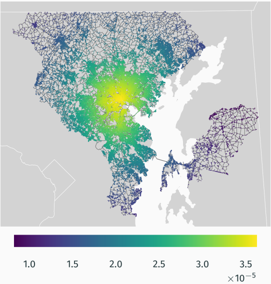


Betweenness Centrality after the collapse

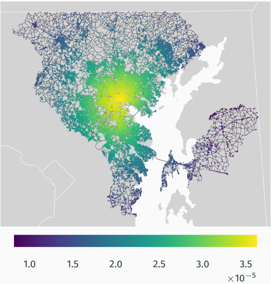


Change in Betweenness Centrality

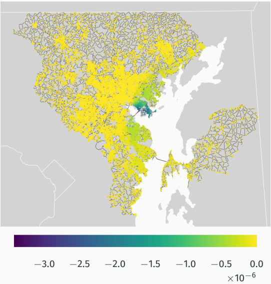
MCA: Closeness Centrality



Closeness Centrality before the collapse

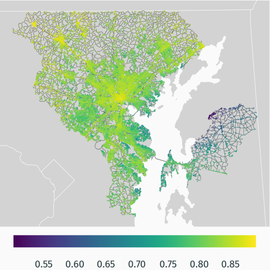


Closeness Centrality after the collapse

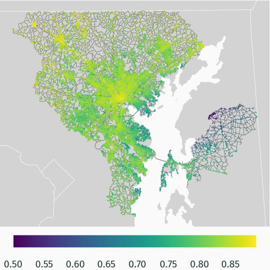


Change in Closeness Centrality

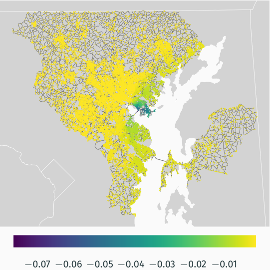
MCA: Straightness Centrality



Straightness Centrality before the collapse



Straightness Centrality after the collapse



Change in Straightness Centrality

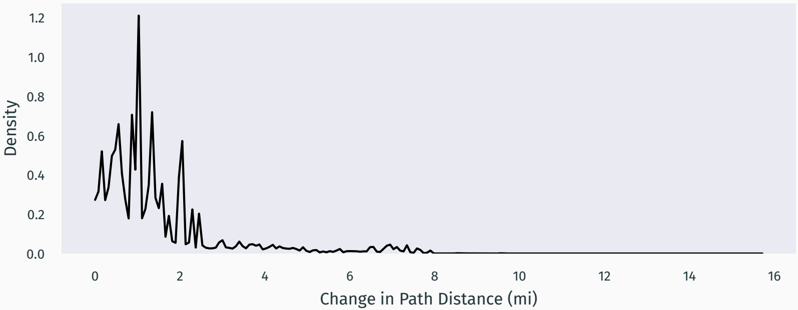
Impacted Shortest Paths (1/3)

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

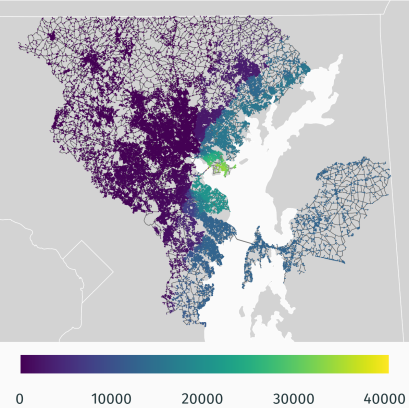
Count	Mean	St. Dev.	Min	25%	Median	75%	Max
4.750×10^8	1.525	1.514	1.864×10^{-6}	0.559	1.049	2.018	15.716

Unit: Miles

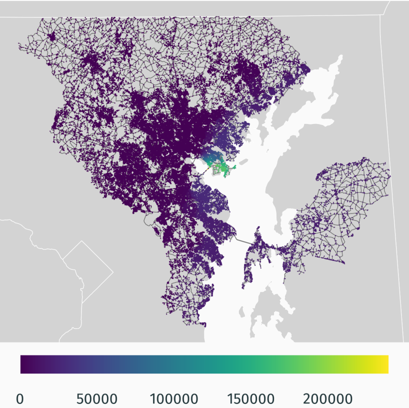
Impacted Shortest Paths (2/3)



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 devisions, which are standard in attack literature (Xeumei and Xiaochen 2010)

Further Work

Future work could

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

Questions?

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