Resilient Livelihoods: The Vulnerability of Commutes to Street Network Disruption

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16. Abstract

Commutes connect people to their livelihoods, and commutes' vulnerability to disruption impacts individual quality of life and societal economic outcomes. The literature suggests that street network design influences trip vulnerability to man-made and natural disasters, but it focuses on evacuation planning and network performance at large—revealing less about empirical trip patterns, and particularly commutes. This study investigates how different types of street network disruptions impact commutes, then estimates relationships between street network design and commute vulnerability. We simulate 266 million empirical commute trips across 387 U.S. metro areas alongside three different disaster type simulations, then model trip outcomes as a function of local network and trip characteristics. All else equal, we find that fewer streets per node and higher circuity each consistently predict greater odds of trips becoming disconnected and greater changes in length for rerouted trips. These design characteristics interact with natural elements of urban geography to determine sustainability outcomes. We argue that these offer key opportunities for urban planners and policymakers intervening into existing or designing new street networks for more secure and sustainable livelihoods after unexpected events.

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The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

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Abstract

Commutes connect people to their livelihoods, and commutes' vulnerability to disruption impacts individual quality of life and societal economic outcomes. The literature suggests that street network design influences trip vulnerability to man-made and natural disasters, but it focuses on evacuation planning and network performance at large—revealing less about empirical trip patterns, and particularly commutes. This study investigates how different types of street network disruptions impact commutes, then estimates relationships between street network design and commute vulnerability. We simulate 266 million empirical commute trips across 387 U.S. metro areas alongside three different disaster type simulations, then model trip outcomes as a function of local network and trip characteristics. All else equal, we find that fewer streets per node and higher circuity each consistently predict greater odds of trips becoming disconnected and greater changes in length for rerouted trips. These design characteristics interact with natural elements of urban geography to determine sustainability outcomes. We argue that these offer key opportunities for urban planners and policymakers intervening into existing or designing new street networks for more secure and sustainable livelihoods after unexpected events.

Resilient Livelihoods: The Vulnerability of Commutes to Street Network Disruption

Executive Summary

This research examines the impact of disruptions in street networks on daily commutes, particularly in relation to the livelihoods of millions of workers. It simulates 266 million commute trips across 387 U.S. metropolitan areas, and identifies that the type and location of disruptions significantly influence the number of trips that become disconnected or rerouted. Notably, a centrality-based disruption (removing 10% of the most crucial nodes) resulted in the most severe consequences, fully disconnecting 67% of commutes. While random disruptions had a lesser impact on total disconnections, they still affected nearly all trips. In contrast, flooding-based disruptions (simulated based on elevation) resulted in fewer overall disconnections but disproportionately affected coastal or riverine communities.

A key finding is that street network design plays a pivotal role in commuting resilience. Commutes traveling on networks with limited streets per intersection, highly circuitous roads, and heavy reliance on specific chokepoints—such as critical bridges or freeway interchanges—face greater risks of disconnection or substantial increases in travel distances. This vulnerability is particularly pronounced for longer commutes, which depend on extended segments of uninterrupted infrastructure. Conversely, more interconnected road networks and shorter travel distances consistently correlate with enhanced resilience.

Given that commutes connect individuals to workplaces, systemic disruptions have far-reaching economic consequences. While some workers may adapt by working from home, lower-income households and essential workers relying on physical presence and limited transportation options often bear disproportionate burdens. To mitigate these effects, planners and policymakers can implement strategies such as strengthening critical nodes, diversifying route options, and promoting balanced jobs-housing relationships. Integrating flood prevention measures, redundant routing, and active monitoring systems also helps safeguard critical corridors from natural or man-made crises.

Protecting people's daily commutes extends beyond convenience. It underpins household incomes, promotes equitable access to employment opportunities, and facilitates a faster recovery from unexpected shocks. By acknowledging and addressing these vulnerabilities, cities can foster a more resilient, inclusive, and sustainable urban future.

Introduction

In the early hours of Saturday, 11 November 2023, a fire broke out at a pallet yard under Downtown Los Angeles's elevated Interstate 10 freeway (Hassan and Jolly 2023). Igniting a nearby cache of alcohol-based sanitizer stored during the Covid-19 pandemic, the resulting inferno compromised the freeway's support columns (Solis et al. 2024). The following Monday, California governor Gavin Newsom declared a state of emergency and announced that the freeway segment—one of the nation's busiest—would close indefinitely for repairs (Hassan and Jolly 2023). Los Angeles residents received citywide cell phone alerts about the closure and were told to expect overwhelming traffic congestion. That morning, a local media outlet spoke with commuters about the closure's impact (Alonso et al. 2023). One said it was "adding about 10 minutes from my day and then it's just more anxiety and stress than the normal morning." Another commuter bluntly stated, "I'm miserable."

Street networks underlie these daily commutes that physically connect people with their livelihoods. Unexpected disruptions to this infrastructure can cause widespread economic harm. Heavy rains or sea level rise can flood streets. Earthquakes or fires can sever highways or block them with debris. Warfare or terrorism can target important chokepoints to disconnect parts of the city. Efficient access to one's livelihood has enormous economic ramifications for both individual quality of life and for society as it recovers from such an event. The literature suggests that street network design can result in more—or less—performant, resilient, and robust infrastructure (Mattsson and Jenelius 2015; Sharifi 2019; Schuster, Polleres, and Wachs 2024). However, the current literature focuses on real-world disruption case studies or overall network performance, and tells us less about the vulnerability of daily commutes vis-à-vis generalizable relationships between network design characteristics and disproportionate impacts (Allan et al. 2013; Ma et al. 2016; Zheng et al. 2024; Kuncheria et al. 2024). Planners require a better understanding of these relationships—particularly so in today's ever more dangerous world—for better evidence-informed urban planning.

This study takes up this challenge to ask where are commutes most vulnerable to street network failure in the U.S.? What network design and trip characteristics explain this variation in vulnerability? We model the street networks of 387 U.S. metropolitan statistical areas (MSAs) to simulate 66 million workers' commutes before and after network disruptions of three different types: 1) targeted attacks on "important" parts of the network, 2) elevation-based flooding disasters, and 3) random failures during high spatial entropy disasters. We then model commute impacts as a function of local network design and trip characteristics plus a full set of controls. All else equal, we find disruption type shapes the effects, but so do network design and urban geography more broadly. We argue that, although disasters are stochastic, planners can keep people better connected to their livelihoods by shifting the locations of homes and workplaces over time and emphasizing specific design characteristics that foster resilience when building new or retrofitting existing urban transport networks.

The rest of this article is organized as follows. First we summarize the literature around commutes and network vulnerability to disruption, noting limits to the current empirical understanding of commutes. Next we describe our data sources and GIScience methods to answer our research question. Then we present our results before concluding with a discussion of commutes' vulnerability to disruption and how planners can foster more resilient mobility infrastructure.

Background

Commutes connect people to their livelihoods. These routine trips rely on street networks and tend to span longer distances than other trips. In the U.S., 92% of commuters drive alone to work and the average commute spans 22 kilometers, above the average for all trips (Bricka et al. 2024). Despite the recent growth of remote work, the majority of commuters still travel to their workplace by car (Burrows and Burd 2024).

Due to the U.S.'s reliance on cars, and in turn street networks, secure and sustainable livelihoods are vulnerable to infrastructure disruptions from natural disasters, random incidents, and targeted attacks. Such disruptions impact commutes by making parts of the street network inefficient or impassable, potentially for extended periods of time (Misra et al. 2020; Rajput et al. 2023; Gong et al. 2024). For example, the 2007 collapse of Minneapolis's Interstate 35W Mississippi River Bridge impacted surrounding traffic volumes for months (He and Liu 2012). Short-term street network disruptions can disconnect or reroute commutes, increasing traffic congestion and travel time (Jacobs et al. 2018). Long-term disruptions can harm workers' quality of life, disconnect people from their livelihoods, and cause economic hardship (Bukvic et al. 2021; Campbell et al. 2021).

However, not all commutes are equally vulnerable to street network disruptions. Exposure depends on several urban factors. The first is the spatial distribution of jobs and housing: for example, commutes are more susceptible to flooding in cities with employment clustered in low-lying areas near water (Bukvic et al. 2021; Kasmalkar et al. 2020). Second, even with the same spatial distribution of jobs and housing, commuting patterns can exacerbate street network disruptions' impacts. Long-distance commutes rely more heavily on stable network function compared to short local trips (Morelli and Cunha 2021). Third, the ability to re-route a trip after a disruption depends on street network design characteristics (Sharifi 2019; Yu and Gayah 2020). When the original shortest path minimizing a commuter's impedance function is no longer feasible, commuters that can find at least one alternative path to their destination can at least stay connected, though less efficiently so.

In other words, these resilience-related post-disaster outcomes—such as disconnectedness and inefficiency—depend in part on urban geography and in part on street network design. For example, trips along street networks with greater redundancy and connectedness are more likely to remain connected even when parts of the network fail (Shang et al. 2020; Santos et al. 2021; Zhang, Miller-Hooks, and Denny 2015). Chokepoints in particular represent brittle failure points: trips are more vulnerable to disruption when they rely on nodes of extremely high importance (Boeing and Ha 2024; Kermanshah and Derrible 2017). For example, a trip that crosses a river could become disconnected if the only bridge is disrupted. Thus, the geometric and topological characteristics of street networks can contribute to trips remaining completeable (with some increase in trip length) or becoming disconnected (Kermanshah and Derrible 2016, 2017).

Many studies have thus modeled network vulnerability (e.g., Murray 2013; Gao, Barzel, and Barabási 2016; Grubesic et al. 2008). This recent literature has investigated the consequences of street network failure, but current theory is largely limited to the system's overall functionality. For example, many studies simulate the impacts on street network performance from low spatial entropy targeted attacks on important infrastructure (Lin, Chen, and Liang 2018; Ozuduru et al. 2021; Wang, Antipova, and Porta

2011; Yoshimura et al. 2021), medium spatial entropy natural disasters such as floods (Kasmalkar et al. 2020; Liao et al. 2023; Li and Yan 2024), and high spatial entropy random events (Martín et al. 2021; Santos et al. 2021). These studies use centrality measures to identify important infrastructure and elevation data to identify low-lying areas at higher risk of flooding, and consistently find that disruptions to high centrality network components have the greatest repercussions on networks' overall connectedness and efficiency (e.g., Aydin et al. 2018; Sharifi 2019; Akbarzadeh et al. 2019; Jenelius and Mattsson 2012; Kermanshah and Derrible 2016; Martín et al. 2021).

However, our current empirical understanding of commute vulnerability is often limited to events like flooding and traffic collisions (Chen et al. 2024; Morelli and Cunha 2021). For example, (Kermanshah and Derrible 2017) identify the impact of floodplains on commutes using the Longitudinal Employer-Household Dynamics (LEHD) dataset, and find that flooding can disconnect over half of the commutes in New York and Chicago, with the greatest impacts when high centrality edges are flood-prone. Similarly, (Kasmalkar et al. 2020) simulate coastal flooding in the San Francisco Bay Area, finding that a 3-foot water level rise disconnects 12% of commutes, with some shoreline census tracts experiencing up to 50% disruption. Another case study in the San Francisco Bay Area examines the effects of the Richmond-San Rafael Bridge closure on commute flows and traffic speed, volume, and delays (Kuncheria et al. 2024).

This body of literature tells us about the impacts of street network disruptions and the characteristics of resilient street networks. However, its commute-specific studies rely on case studies to measure disaster impacts in individual cities, and its studies that characterize street network resilience overall tell us little about trip-specific—let alone commute-specific—network features. This is important: earthquakes, floods, or targeted attacks can destroy parts of our transport infrastructure and disconnect people from the livelihoods on which they rely. Better knowledge of the relationships between street network characteristics and the vulnerability of commutes can help urban planners and engineers design more robust and resilient infrastructure to attenuate post-disaster impacts on economic geography and urban well-being.

Methods

This study advances this literature by answering two intertwined questions about commute vulnerability. First, how do street network disruptions affect access to livelihoods—that is, how do they impact commutes? Second, what are the relationships between street network design characteristics and commute vulnerability? We simulate commutes for over 66 million people in 387 MSAs across 50 U.S. states. We then simulate three types of street network disruptions: targeted attacks on important nodes, flooding of low-lying nodes, and high-entropy destruction of random nodes. After each disruption, we analyze how commute trips become 1) disconnected, 2) connected but re-routed a longer distance because the original shortest path is no longer feasible, or 3) unaffected. These simulations examine trip feasibility and path efficiency, rather than traffic volumes or segment capacity.

Data Sources

We model the drivable street networks of 387 U.S. MSAs using the OSMnx Python package and OpenStreetMap data. Then we derive home-to-work commute trips' origin-destination (OD) pairs using the most-recent Census Transportation Planning Products (CTPP) data. While a few sources for commute data exist, we use CTPP because it represents actual trips, excludes remote work, and includes transport mode. Next, we attach elevation data to each node in the street network models automatically using OSMnx and data from the Google Maps Elevation API. Finally, we use the most-recent LEHD data to determine the count of workplaces at the census block level to empirically identify central business districts (CBDs), following Giuliano et al. (2022)'s approach, as described below.

Commute and Network Disruption Simulations

We simulate commute trips between more than 3.2 million unique OD pairs from the CTPP data, representing commutes of more than 66 million people in 387 MSAs. These trips represent individuals who drive alone to work and commute between different census tracts, covering more than 45% of all workers in the U.S. The OD pairs from the CTPP data are aggregated at the census tract level, and each trip's origin and destination is resolved to the nearest node in the street network for solving shortest paths by minimizing distance traveled with Dijkstra's algorithm. This approach is imperfect (it does not capture traffic congestion, for instance), but it is ubiquitous in the literature to approximate travel patterns. All trips are feasible in the original undisrupted street network model.

Next, we simulate these commute trips after disrupting the street network by removing 10% of its nodes according to one of three disruption types. This assumes a moderate level of network disruption while still allowing for meaningful comparisons across MSAs. It also offers a middle-ground for comparison with the literature's standard of removing 5-15% nodes (e.g., Duan and Lu 2014; Santos et al. 2021). In the first type, we eliminate "important" nodes (operationalized as node betweenness centrality), simulating a targeted attack on the street network. In the second type, we remove the lowest-elevation nodes, as a proxy for floods affecting low-lying areas. The Federal Emergency Management Agency real-world delineates U.S. flood zones: however, these zones tend to correlate closely with low-lying areas. As such, we directly use elevation data to measure relative disruption magnitudes across MSAs. In the third type, we randomly eliminate nodes to simulate high spatial entropy events such as traffic collisions, earthquakes, or unexpected infrastructure failures. This serves as a theoretical baseline for the disruptions as it exhibits a uniformly stochastic spatial distribution across each study site's network.

Then, we analyze the outcome of each street network disruption on each commute trip. We set aside "nullified" trips with the origin or destination node itself being eliminated (obviating the trip itself). This leaves us three trip outcomes of interest to analyze in stages. First, the "disconnected" trips are those where there no longer exists any network path between extant origin and destination node pairs. Outside of these nullified and disconnected trips, all other trips remain connected between origin and destination. However, some remain "unaffected" (i.e., the shortest path remains the same after the disruption), whereas others are "rerouted" to new (inherently longer) shortest paths due to disruption of the original shortest path. In summary, this analysis sets aside nullified trips then examines three trip outcomes in stages: disconnected, unaffected, and rerouted trips.

Table 1. Variables' descriptions and data sources (Note: † indicates values measured for local street networks within a 500 meter buffer of each trip's path in the original pre-disruption network.)

Variable	Description
Disconnected	Dummy variable: 1 = trip is disconnected after disruption, 0 = trip remains connected. Measured for non-nullified trips only. Derived from simulation.
Rerouted	Dummy variable: 1 = trip is rerouted after disruption, 0 = trip length remains the same. Measured for connected trips only. Derived from simulation.
Pct Δ Length	Percent change in trip length after disruption. Measured for rerouted trips only. Derived from simulation.
Avg streets-per-node†	Measure of network connectedness: average number of streets per node (intersection/dead-end). Derived from OSM data.
Circuity†	What percent greater is the sum of the network's curvilinear street lengths to the straight-line distances between nodes. Derived from OSM data.
Chokepoint score†	Difference between the 500 meter buffer's max and network's mean node betweenness centrality, in units of standard deviations. Derived from OSM data.
Disruption impact†	Percentage of nodes removed by disruption simulation. Derived from OSM data and our simulation.
Importance†	Relative importance of removed nodes by disruption simulation: ratio of mean betweenness centrality of removed nodes to mean betweenness centrality of not-removed nodes. Derived from OSM data and simulation.
Hilliness†	Standard deviation of node elevations. Derived from OSM data, Google Maps Elevation API, and simulation.
Flood safety†	Relative elevation of trips: ratio of mean node elevations within trip's 500 meter buffer to mean node elevations within MSA. Derived from OSM data, Google Maps Elevation API, and simulation.
Intersect density†	Number of intersections per km2. Derived from OSM data.
Trip length	Length of the shortest path in the original (unperturbed) network (km). Derived from OSM data and simulation.
Dist between O and CBD	Euclidean distance between the origin and CBD (km). Derived from OSM, CTPP, LEHD data.
Dist between D and CBD	Euclidean distance between the destination and CBD (km). Derived from OSM, CTPP, LEHD data.
Trip direction	Ratio of "Dist between O and CBD" to "Dist between D and CBD." Value 1 indicates commute toward the CBD and 1 indicates a reverse commute. Derived from OSM, CTPP, LEHD data.

To analyze these impacts, we calculate geometric and topological measures of the local street network along each commute. Table 1 describes these measures. For each trip, we select the network nodes and edges within a 500-meter buffer around its path then calculate three key variables of interest: the average streets-per-node count (i.e., a measure of connectedness), circuity (i.e., a measure of efficiency), and chokepoint score (i.e., a measure of over-reliance on single points of failure). This buffer approach follows the literature (e.g., Forsyth et al. 2012) by capturing the trip's exposure to local street network characteristics that constrain connectedness along the route: smaller buffers might miss subtle variations in network structure near a route, while larger buffers might lose the focus on the immediate environment. The chokepoint score, C_t, adapts Boeing and Ha (2024)'s measure, indicating nodes with high betweenness centrality relative to the entire MSA's network, defined as:

$$C_t = \frac{max(b_u \forall u \in G_t) - (\overline{b_u} \forall u \in G)}{\sigma(b_u \forall u \in G)}$$

where b_u is the betweenness centrality of node u, G is the graph model of the network as a whole, and G_t is a subgraph induced on the nodes intersecting a 500-meter buffer around trip t's original path geometry. Additionally, we calculate intersection density (i.e., non-dead-end nodes per km^2), hilliness (i.e., the standard deviation of node elevations), and an indicator of t's "flood safety", F_t, defined as:

$$F_t = \frac{\overline{e_u} \forall u \in G_t}{\overline{e_u} \forall u \in G}$$

where e_u is the elevation of node u. Next we calculate each trip's network length from origin to destination. Then we quantify the location of trips relative to the nearest CBD. While the location of principal cities or city halls is often used as a proxy for CBD locations, these methods have limitations due to varying city boundaries and the mismatch between the city halls and employment centers. Therefore, we instead estimate CBD locations using Giuliano et al. (2022)'s method. To summarize, this identifies clusters of adjacent regular hexagons meeting two criteria: 1) employment density of each hexagon exceeds the 95th percentile within the MSA, and 2) the total number of jobs within these adjacent hexagons exceeds 10,000. We apply generous cut-offs to identify CBDs for both small and large MSAs. If multiple employment centers are identified in an MSA, the CBD is defined as the largest of them.

Regression Analysis

We estimate nine regression models to predict three trip outcome response variables across three disruption types, as a function of trip and network characteristics. Just as our trip outcomes above were in three stages (after setting aside nullified trips), so too are our modeled outcomes.

First, models 1, 2, and 3 use weighted logistic regression to predict whether a (non-nullified) trip becomes disconnected after each disruption type. This is a binary outcome where disconnected trips are coded as 1 and connected as 0. Next, models 4, 5, and 6 use weighted logistic regression to model whether a (connected) trip is rerouted after each disruption type. This is a binary outcome where rerouted trips are coded as 1 and unaffected as 0. Finally, models 7, 8, and 9 use weighted least squares to model the (log) percent change in trip length after each disruption type (for the connected but rerouted trips). All nine models' parameters are estimated by weighting each tract-to-tract trip by the number of people who drove alone to work between those tracts.

The predictors contain the three key variables of interest discussed above, plus a set of control variables including trip length, the distances between the CBD and the origin/destination, the direction of the trip (i.e., the distance between origin and CBD divided by the distance between destination and CBD) to identify standard versus reverse commutes, intersection density, the percentage and importance of removed nodes, hilliness, and the trip's average elevation relative to the entire MSA. These variables are described in Table 1. In the regression models, they are log-transformed as needed for a better linear fit.

Findings

Disruptions' Impacts on Commutes

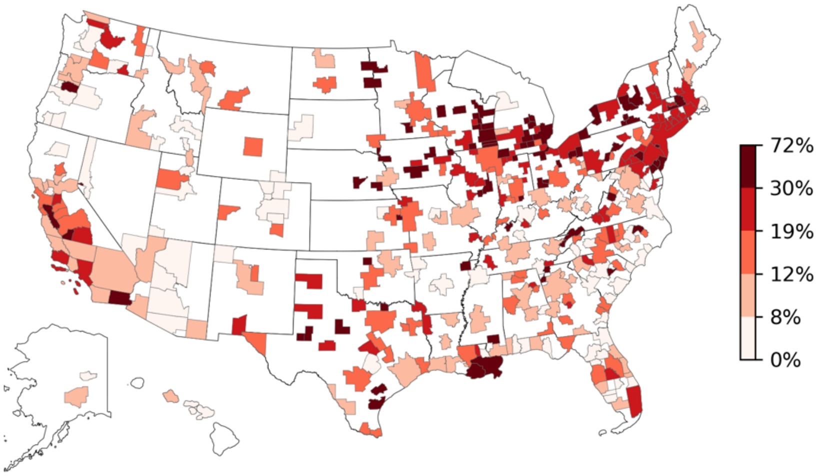
Table 2 describes the impact of street network disruptions on commutes, categorized into four outcomes: nullified, disconnected, unaffected, and rerouted. The unaffected and rerouted trips collectively represent connected commutes. Figure 1 shows the share of commutes remaining connected after the three disruption types affecting 10% of nodes. Table 3 presents variables' mean values across the three disruption types and outcomes of interest.

Table 2. The disruption types' commute trip outcomes

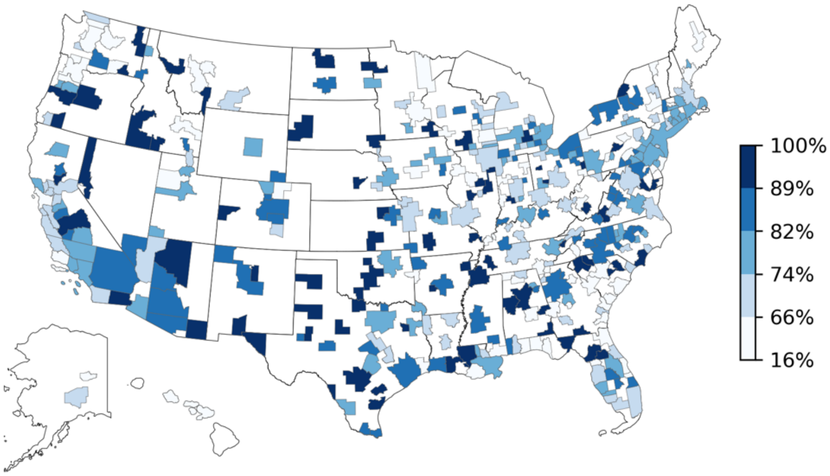
	Centrality		**Elevation**		**Random**	
	Count	Pct	Count	Pct	Count	Pct
Nullified	10,516,712	15.8%	12,811,118	19.2%	12,804,382	19.2%
Disconnected	44,696,279	67.1%	3,087,541	4.6%	18,018,364	27.1%
Connected	11,368,531	17.1%	50,682,863	76.1%	35,758,776	53.7%
Unaffected	2,656,243	4.0%	40,001,852	60.1%	1,005,317	1.5%
Rerouted	8,712,288	13.1%	10,681,011	16.0%	34,753,459	52.2%

After the centrality-based disruptions, 16% of commutes become nullified and 67% of commuters become disconnected from their workplace by any street network path. Only 17% of commutes remain connected after the disruption, and only 4% are wholly unaffected. Among populous MSAs (i.e., those with over 300,000 commuters), Milwaukee and Buffalo are less impacted, with over 40% of commutes remaining connected in each. In contrast, Phoenix's and Seattle's MSAs have less than 5% of commutes remaining connected. Unaffected trips have lower chokepoint scores and shorter trip lengths than affected (i.e., disconnected or rerouted) trips. Compared to disconnected trips, the rerouted trips are shorter and have more streets-per-node and lower circuity along the shortest path. Disconnected trips have higher intersection densities and proximities to the CBD, indicating that such trips are located in denser, central locations more prone to centrality-based disruption. Finally, the average rerouted commute's trip length increases by 139%.

% trips connected after centrality-based disruption



% trips connected after elevation-based disruption



% trips connected after random disruption

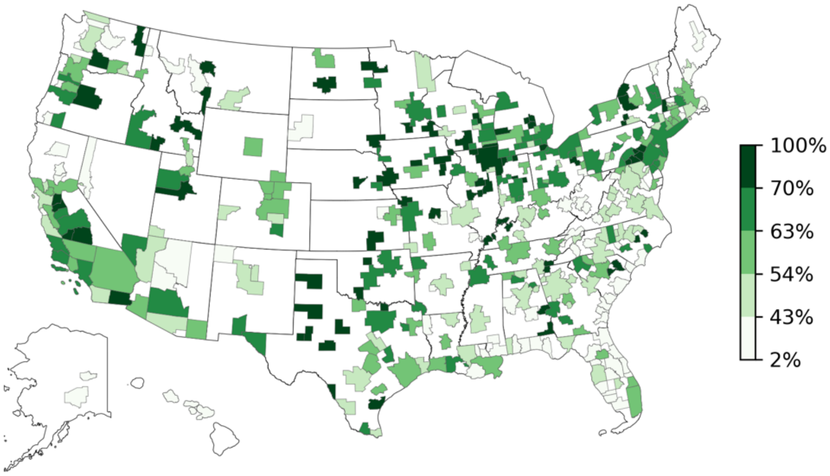


Figure 1. Percent of commutes remaining connected per MSA after each disruption type

After the elevation-based disruptions, 19% of commutes become nullified but only 5% of commuters become disconnected from their workplace by any street network path—much less than centrality-based disruptions. 60% of all commutes remain connected after the disruption, and only 16% are rerouted. The largest impact is seen in the small and flood-prone Hilton Head Island MSA, where only 16% of commutes stay connected. Among populous MSAs, Seattle (58%), Jacksonville (56%), and Portland (54%) show relatively low percentages of post-disruption connected commutes. Disconnected trips feature fewer streets-per-node, more circuitous networks, and lower flood safety compared to rerouted trips. The average node elevations along disconnected trips are only 63% of the entire network's average, suggesting that such trips are disproportionately located in lower-lying areas. Finally, rerouted trips experience a 60% increase in trip length, which is less than centrality-based disruptions.

After the random disruptions, 19% of commutes become nullified and 27% become disconnected. 54% of all commutes remain connected, but only 2% of commutes are unaffected. More than 97% of connected trips are rerouted trips—a much larger proportion than the other two disruption types have. Lesser impacts are observed in MSAs like Chicago, Detroit, and Los Angeles where at least 70% of commutes remain connected. In contrast, less than 40% of commutes in the Orlando and Jacksonville MSAs remain connected. The disconnected trips after have fewer streets-per-node and longer lengths than connected trips. Unaffected commutes have shorter lengths and lower chokepoint scores on average compared to both disconnected and rerouted trips. The rerouted trips' percent change in length (41%) is the smallest among the three disruption types.

Regression Results

Table 4 presents our nine regression models. The first stage of our three-stage modeling predicts the odds of a trip becoming disconnected (versus remaining connected) after a network disruption. Models 1, 2, and 3 all show that commutes along street networks with higher average streets-per-node are more likely to remain connected. For example, all else being equal, a 1-unit increase in average streets-per-node is associated with a 69.3% decrease in the odds of a trip becoming disconnected due to random disruption. In Models 1, 2, and 3, circuity's coefficient estimates are all significant and positive, indicating that trips along more circuitous street networks are more likely to become disconnected. Specifically, a 1-unit increase in circuity is associated with a 4.1%, 5.5%, and 6.2% increase in the odds of a trip being disconnected in the centrality, elevation, and random disruption types, respectively. The chokepoint score shows inconsistent signs across disruption types, but in the centrality-based simulation, a 1-unit increase in the chokepoint score is associated with a 6.8% increase in the odds of a trip becoming disconnected.

Table 3. Variables' weighted mean values, per disruption type and commute trip outcome

	Centrality			**Elevation**			**Random**		
	Disconnected	Unaffected	Rerouted	Disconnected	Unaffected	Rerouted	Disconnected	Unaffected	Rerouted
Avg streets-per-node	2.915	2.915	2.964	2.930	2.902	2.970	2.874	2.946	2.964
Circuity	6.202	6.221	5.712	6.166	6.328	5.632	6.762	5.731	5.614
Chokepoint score	7.560	1.216	4.489	8.294	6.232	8.612	6.889	3.457	7.120
Disruption impact	19.757	2.444	12.951	21.542	0.234	13.238	10.164	8.215	9.911
Importance	33.486	12.376	23.355	1.544	0.103	1.649	1.022	0.830	1.022
Hilliness	17.635	10.442	13.340	18.271	16.453	17.099	18.883	9.324	15.573
Flood safety	0.789	0.670	0.703	0.626	0.926	0.664	0.781	0.707	0.767
Intersect density	30.230	20.040	25.775	27.605	28.212	31.668	26.648	23.271	31.454
Trip length	15.745	5.460	12.112	20.182	12.359	19.587	16.654	4.057	13.479
Dist between O and CBD	17.362	23.444	19.558	17.329	18.176	15.878	21.255	13.022	15.796
Dist between D and CBD	12.121	22.328	15.398	10.679	13.871	9.659	15.088	11.979	10.671
Trip direction	1.348	1.038	1.216	1.490	1.247	1.495	1.332	1.059	1.368
Pct Δ Length	—	—	139.421	—	—	60.464	—	—	40.967

Table 4. Regression model parameter estimates. Models 1–6 are binary logistic regression and models 7–9 are continuous (log) linear regression. * indicates significance at $p < 0.001$.

Variable	**Disconnected=1, Connected=0**			**Rerouted=1, Unaffected=0**			**Pct Δ Length (log)**		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
	Centrality	Elevation	Random	Centrality	Elevation	Random	Centrality	Elevation	Random
Constant	3.678*	-3.809*	-0.879*	-4.632*	-7.689*	-9.062*	4.793*	4.975*	3.893*
Avg streets-per-node	-2.750*	-0.537*	-1.182*	-1.169*	-0.360*	-0.069*	-0.643*	-0.446*	-1.108*
Circuity	0.041*	0.054*	0.061*	0.003*	0.023*	-0.019*	0.022*	0.033*	0.063*
Chokepoint score	0.066*	-0.004*	-0.007*	-0.007*	-0.004*	0.008*	0.040*	0.021*	0.003*
Disruption impact	0.131*	0.079*	0.130*	0.329*	0.740*	0.276*	0.075*	0.064*	0.119*
Importance	0.002*	0.167*	0.035*	-0.000*	0.797*	0.658*	0.001*	0.082*	0.344*
Hilliness	0.001*	-0.008*	0.001*	-0.008*	-0.023*	-0.002*	-0.001*	0.002*	-0.002*
Flood safety (log)	0.119*	-0.044*	-0.031*	-0.001*	-0.078*	0.012*	0.007*	0.032*	0.002
Intersect density (log)	0.801*	0.021*	0.108*	1.146*	0.390*	1.430*	0.101*	-0.221*	0.054*
Trip length (log)	0.373*	0.691*	0.343*	2.146*	1.839*	2.539*	-0.266*	-0.489*	0.096*
Dist. between O and CBD (log)	-0.199*	-0.219*	0.363*	-0.185*	-0.207*	-0.183*	-0.187*	-0.432*	0.122*
Dist. between D and CBD (log)	0.028*	0.028*	-0.127*	0.002	-0.179*	0.193*	0.181*	0.348*	-0.082*
Trip direction (log)	0.016*	0.136*	-0.270*	0.004	-0.063*	0.336*	0.157*	0.420*	-0.088*
R^2	0.276	0.246	0.059	0.516	0.702	0.383	0.137	0.244	0.132
n	2,748,191	2,593,220	2,647,601	510,301	2,427,723	1,786,073	413,354	611,163	1,749,183

Weighted n	56,064,810	53,770,404	53,777,140	11,368,531	50,682,863	35,758,776	8,712,288	10,681,011	34,753,459

The second stage of our three-stage modeling predicts the odds of a connected trip being rerouted (versus remaining unaffected) after a network disruption. Higher average streets-per-node are consistently associated with lower odds of rerouting. All else equal, a 1-unit increase in circuity is associated with a 68.9%, 30.2%, and 6.7% decrease in the odds of a trip being rerouted across the three disruption types. Circuity's coefficient estimate is positive in Models 4 and 5, indicating that trips along circuitous networks have lower odds of remaining unaffected. Unaffected trips after random disruption account for only 1.5% of all commutes and have particularly short average lengths, suggesting that these are local trips located in areas with circuitous networks and are largely unaffected by random disruption. Rerouted trips have higher chokepoint scores on average compared to unaffected trips (Table 3), and in Model 6, a 1-unit increase in the chokepoint score is associated with a 0.8% increase in the odds of a trip being rerouted. However, the chokepoint score again shows inconsistencies, with negative coefficients in Models 4 and 5, partly explained by 1) unaffected commutes after centrality-based disruptions are often short local trips with some chokepoint within their 500-meter buffer but not in their shortest path, and 2) elevation-based disruptions often target commutes with lower chokepoint scores, particularly in regions where low-lying nodes are located in peripheral areas.

The third stage of our three-stage modeling predicts the change in trip length for the connected rerouted trips. The increase in trip length is consistently less for rerouted commutes along networks with more streets-per-node. All else equal, after the three disruption types, a 1-unit increase in average streets-per-node is associated with 64.3%, 44.6%, and 110.8% increases in the trip length's percent increase. Circuity's coefficient is consistently positive in Models 7, 8, and 9. All else equal, a 1-unit increase in circuity is associated with 2.2%, 3.3%, and 6.3% increases in the trip length's percent increase. That is, disruptions result in shorter re-routes in less circuitous networks. The chokepoint score also shows consistently positive signs across these three models. All else equal, after the three disruption types, a 1-unit increase in the chokepoint score is associated with 4.0%, 2.1%, and 0.3% increases in the trip length's percent change.

Case Study

To unpack these relationships, we take a deeper look at 12 individual MSAs' outcomes. These 12 MSAs represent a range of sizes and outcomes, from modest to extreme, after centrality- and elevation-based disruptions. Here we do not focus on random disruptions, which instead offer a theoretical baseline. Table 5 presents their numerical outcomes and characteristics, and Figures 2, 3, and 4 illustrate their commutes' simulated routes grouped by outcome.

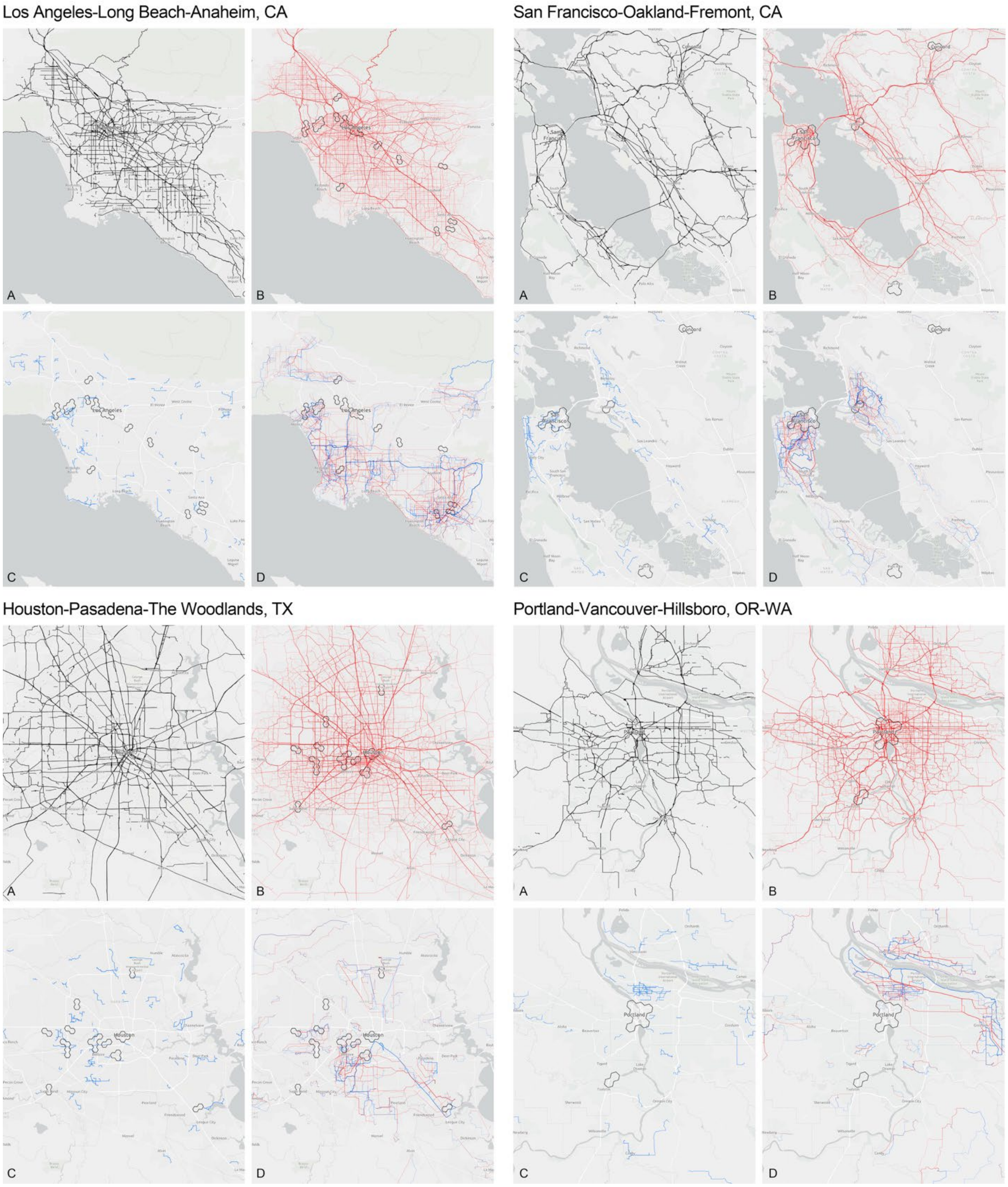
Figure 2. Outcomes of 10% centrality-based disruption simulations in Des Moines, Philadelphia, Las Vegas, and Phoenix showing: a) disrupted nodes, b) disconnected trips, c) unaffected trips, d) rerouted trips. Red lines are shortest paths before disruption and blue lines are shortest paths after disruption

Figure 2 reveals divergent outcomes after centrality-based disruption: Las Vegas and Phoenix fare worse than Des Moines and Philadelphia. Over 70% of commutes become disconnected in Las Vegas and

Phoenix, compared to only 42% in Des Moines and 63% in Philadelphia. Instead of disconnecting, Des Moines (29%) and Philadelphia (18%) have much higher percentages of rerouted commutes than Las Vegas (1.7%) and Phoenix (2.4%). Why? Figure 2 shows that disconnected trips in all four MSAs usually traversed high centrality areas like the CBD and regional subcenters. Meanwhile, unaffected trips tend to occur around the urban periphery (i.e., a low centrality area) or are short trips that by luck occur where few others do. While the rerouted trips in Des Moines show similar pre-disruption spatial patterns as the disconnected trips, they have very different post-disruption outcomes. Unlike the disconnected trips, the rerouted trips are able to concentrate into a couple of unaffected alternate paths to remain connected after the disruption, whereas the disconnected trips (by definition) could not. Comparing Des Moines to Las Vegas and Phoenix helps explain these outcomes. Their commute lengths are similar and there is no significant difference in jobs-housing geography—the difference is in our three key street network design variables of interest. Des Moines has higher average streets per node, lower chokepoint scores, and lower circuity than either Las Vegas or Phoenix, which is consistent with the regression analysis that found that these correlate with remaining connected.

Figure 3 reveals a story about urban geography and polycentricity. Los Angeles and San Francisco have relatively better outcomes than most MSAs but interestingly also have relatively high chokepoint scores. How does this happen? Los Angeles's highest chokepoint scores locate around the 101, 5, and 10 freeways ringing downtown, but the MSA has many other regional job subcenters as seen in Figure 3 that do not require freeway access. Los Angeles's downtown is its largest job center and its commutes depend heavily on high-centrality regionwide freeways that fail after this disruption, nearly fully disconnecting the downtown. However, Los Angeles is famously an "edge city" with many regional subcenters that attract local commutes without relying on those high-centrality freeways. Similarly, San Francisco's highest chokepoints locate around its bay-spanning bridges, but many of its commutes do not rely on these. The centrality-based disruption disconnects commutes that travel along these bridges, whereas those not reliant on bridges remain reasonably well-connected.

In contrast, Houston and Portland have relatively worse outcomes than most MSAs but interestingly have relatively "good" values across our key street network design variables of interest. How does this happen? In Houston, several job subcenters cluster on the westside and the centrality-based disruption disproportionately targets those areas, disconnecting many commutes. Meanwhile, Portland's CBD is in the city center, bisected by the Willamette River, and the centrality-based disruption knocks out these river-spanning bridges and central freeways that commuters need to access the center. In other words, these cities tend to have lower chokepoint scores, high average streets per node, and lower circuity than most street networks, but none of this matters for commutes if the job centers are specifically disconnected from the rest of the city by a targeted attack. To summarize: in Portland and Houston the jobs centers co-locate with the highest centrality nodes, whereas in Los Angeles and San Francisco, they do so less, which allows regional job subcenters to remain connected to local commuters. This is seen perhaps most clearly in comparing Portland directly to Los Angeles: most commuters in Portland commute to its one major job center downtown, but Los Angeles commuters scatter in all directions all over the sprawling MSA's many subcenters.



Los Angeles-Long Beach-Anaheim, CA

San Francisco-Oakland-Fremont, CA

Houston-Pasadena-The Woodlands, TX

Portland-Vancouver-Hillsboro, OR-WA

Figure 3. Outcomes of 10% centrality-based disruption simulations in Los Angeles, San Francisco, Houston, and Portland showing: a) disrupted nodes, b) disconnected trips, c) unaffected trips, d) rerouted trips. Red lines are shortest paths before disruption, blue lines are shortest paths after disruption, and black lines are job center boundaries.

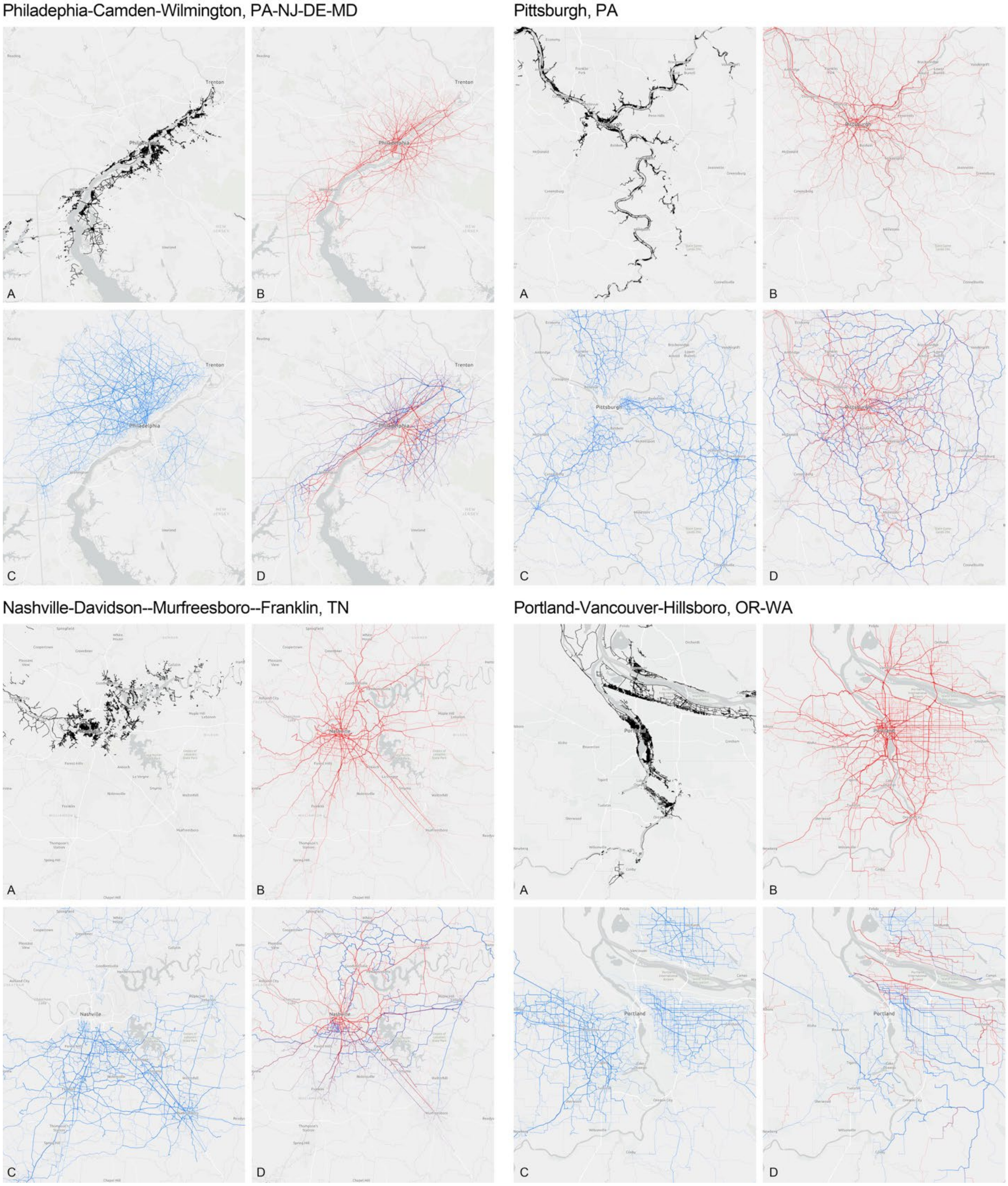


Figure 4. Outcomes of 10% elevation-based disruption simulations in Philadelphia, Pittsburgh, Nashville, and Portland showing: a) disrupted nodes, b) disconnected trips, c) unaffected trips, d) rerouted trips. Red lines are shortest paths before disruption and blue lines are shortest paths after disruption

Table 5. Post-disruption trip outcomes and trip/network characteristics for selected MSAs

MSA	Nullified %	Disconnected %	Unaffected %	Rerouted %	Avg streets-per-node	Circuity	Chokepoint score	Avg commute length
Centrality-based disruption								
Des Moines-West Des Moines, IA	24.7	41.6	4.4	29.4	3.09	4.43	6.62	16.14
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	13.8	62.6	6.0	17.6	2.99	6.62	6.18	17.79
Las Vegas-Henderson-North Las Vegas, NV	15.4	78.0	4.9	1.7	2.87	5.13	8.68	16.51
Phoenix-Mesa-Chandler, AZ	24.6	71.3	1.7	2.4	2.91	6.67	11.05	23.73
Los Angeles-Long Beach-Anaheim, CA	15.1	63.1	4.6	17.3	2.99	4.73	8.72	19.80
San Francisco-Oakland-Fremont, CA	16.6	66.4	3.9	13.2	2.97	6.17	8.35	19.79
Houston-Pasadena-The Woodlands, TX	12.2	78.8	3.5	5.5	3.02	5.44	7.78	24.27
Portland-Vancouver-Hillsboro, OR-WA	17.0	75.3	2.6	5.1	2.85	5.41	7.61	16.83
Elevation-based disruption								
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	17.8	1.7	63.7	16.7	2.99	6.62	6.18	17.79
Pittsburgh, PA	23.0	2.7	44.6	29.7	2.83	5.74	4.41	15.13
Nashville-Davidson–Murfreesboro–Franklin, TN	18.8	14.3	46.8	20.1	2.82	6.08	7.52	22.99
Portland-Vancouver-Hillsboro, OR-WA	30.1	15.6	47.2	7.2	2.85	5.41	7.61	16.83

Finally, Figure 4 illustrates elevation-based disruptions in the Philadelphia, Pittsburgh, Nashville, and Portland MSAs. These MSAs all have rivers at their centers, which are in turn the lowest-elevation parts of the city, and their non-river-crossing commutes remain mostly unaffected. However, fewer than 3% of commutes become disconnected in Philadelphia and Pittsburgh, whereas over 10% become disconnected in Nashville and Portland. Why? All four MSA's city-center bridges are destroyed in the simulated flood. But one peripheral bridge in Philadelphia and two in Pittsburgh remain intact, allowing cross-river commuters to still find an (long and inconvenient but feasible) alternate route. These intact bridges are far upriver at higher elevations. Portland and Nashville have no equivalent within their MSAs: all of their bridges (or the bridges' connector links) have at least one node at low enough elevation to be destroyed. This is particularly striking in Portland, where the few unaffected commutes become divided into three disconnected sections by the Willamette and Columbia rivers.

Grocery Store Access Changes Upon Disruptions

We examine the changes in accessibility to grocery stores following disruptions in street networks. For each MSA, we retrieve street network data from OpenStreetMap and simulate accessibility using the Pandana package. This process begins by identifying nodes representing grocery store locations, based on OpenStreetMap tags such as "grocery," "greengrocer," and "supermarket." Using the node closest to each census tract's centroid, we assess accessibility using two metrics: (1) the number of grocery stores reachable within a 5 km travel distance, and (2) the travel distance (in km) to the nearest grocery store. To simulate the effects of network disruptions, we repeat the process after removing 10% of nodes, using betweenness centrality, elevation, and random criteria. The results are displayed in boxplots, showing the population-weighted averages across 387 MSAs. Additionally, the outcomes are compared between White individuals and those of other racial groups.

Figure 5 presents the average number of grocery stores accessible within a 5 km travel distance across MSAs, before and after network disruptions. In the undisturbed state, individuals can access an average of three grocery stores. This figure, however, falls to fewer than one grocery store when the top 10% of nodes with the highest betweenness centrality values are removed. The removal of low-lying nodes leads to only marginal changes in cumulative accessibility, while random perturbations (serving as the baseline) show moderate impacts, reducing the median number of accessible grocery stores to less than two. Additionally, the results indicate that the White population experiences slightly lower grocery store access, whereas populations of other races demonstrate higher accessibility compared to the total population.

Figure 6 shows changes in the trip distance to the nearest grocery store. In the unperturbed state, the median trip distance of population weighted average is approximately 2.5km. When high-centrality nodes are disrupted, the trip distance increase up to 5.8km, suggesting that trip distances increase by more than 100%. Similar to the findings in Figure 5, disruptions to low-lying nodes result in minimal changes in trip efficiency. The comparison between White populations and those of other races reveals that the trip distance to the nearest grocery store is shorter for non-White populations. Moreover, the impact of network perturbations of three types on trip distance was similar between White and non-White populations. We acknowledge that the ideal approach would be to measure the trip distance to the nearest grocery store using fully disaggregated locations. However, for ease of computation, our analysis utilizes the centroid of each census tract as a proxy for location.

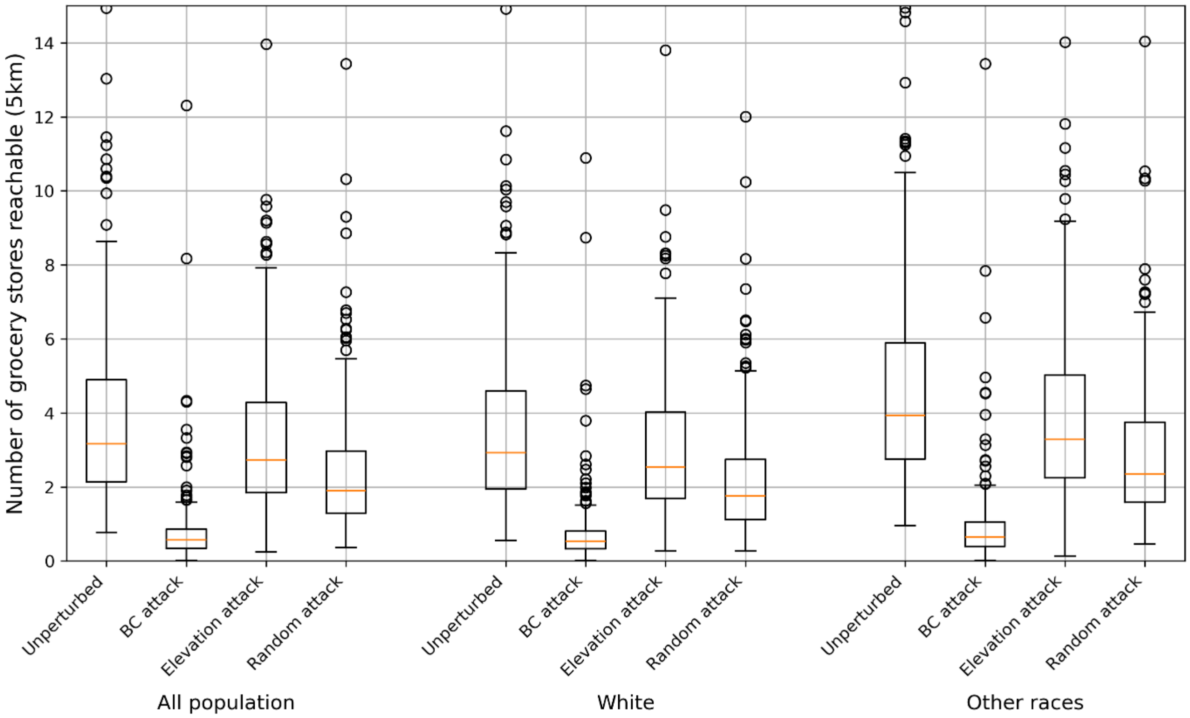


Figure 5. Cumulative accessibility results per MSA by disruption types and population groups (all, White, and other races). Each MSA's cumulative accessibility is calculated by using population-weighted average of census tracts.

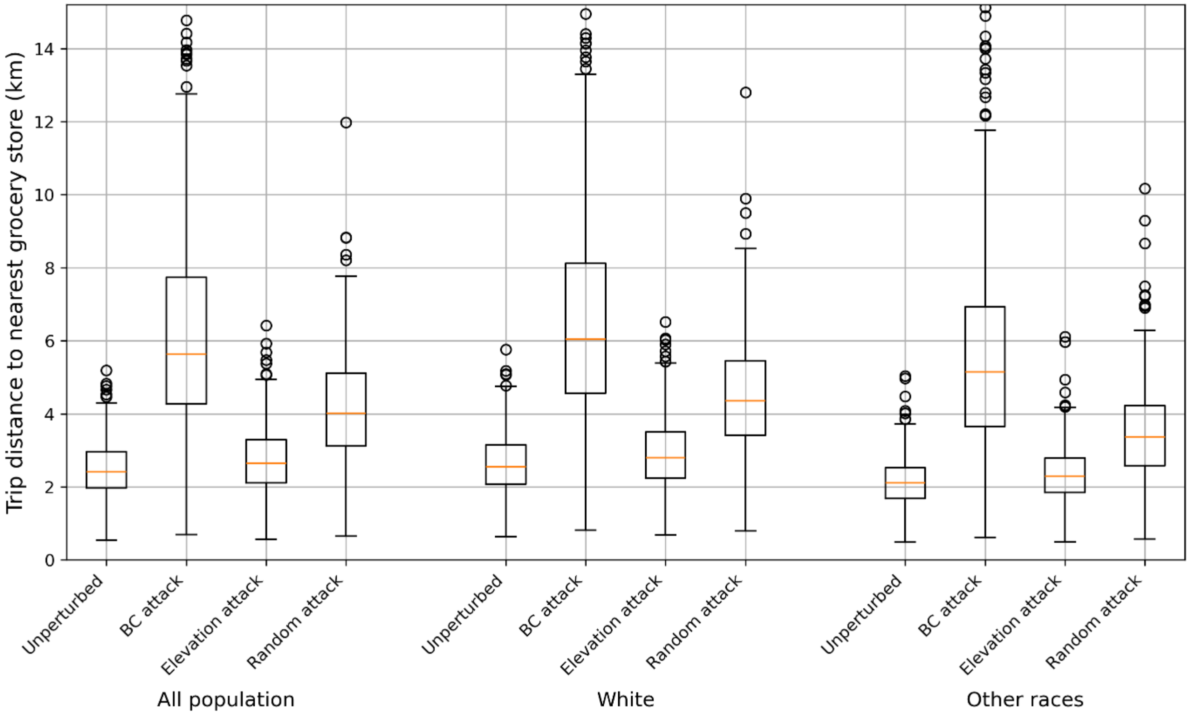


Figure 6. Efficiency of trips to nearest grocery store results per MSA by disruption types and population groups (all, White, and other races)

There are several limitations to this analysis. First, the use of OpenStreetMap data to identify grocery store locations may introduce inaccuracies, particularly in smaller MSAs where crowdsourced data can be less precise. Second, during disruptive events, individuals may not solely depend on large grocery stores or supermarkets for food access, as smaller neighborhood stores—excluded from this study—could still provide alternative sources. Third, our accessibility measures are based on distance alone, without accounting for travel mode or travel time, which may affect the actual ease of access. Lastly, the network disruptions modeled using centrality and elevation are theoretical and may not fully represent real-world scenarios. These disruptions assume large-scale attacks on the network, but the probability of 10% of nodes being compromised is highly unlikely in practice.

Discussion

Commutes connect people to their livelihoods: economic well-being after a street network disruption depends on commutes' resilience. How do unexpected street network disruptions affect commutes, and what are the relationships between street network design and vulnerability to disruption? This study simulated 266 million commute trips across 387 U.S. MSAs before and after simulations of three different types of disasters: centrality-based (representing targeted attacks on important transport infrastructure), elevation-based (representing flooding of low-lying areas), and random (representing high spatial entropy disasters as a theoretical baseline).

Our findings show how the disruption type shapes the effects. Across all MSAs, the centrality-based disruption has particularly large consequences: disrupting just 10% of nodes impacts 96% of all commutes and fully disconnects 67%. Meanwhile, the random disruption impacts 98% of commutes but disconnects only 27%, and the elevation-based disruption impacts just 40% of commutes and disconnects just 5%. Our findings also show that the three key street network design variables of interest have significant relationships with post-disaster commute trip outcomes. Consistently across all nine regression models, lower intersection "connectivity" (i.e., average streets per node) significantly predicts greater odds of a trip becoming disconnected or rerouted, as well as greater length increases for rerouted trips, all else equal. Greater network circuity shows the same significant relationships with those outcomes, across eight of the nine models, all else equal. Moreover, all three variables of interest have consistent signs and significance across all three models predicting rerouted trips' change in length: lower average streets per node, higher circuity, and higher chokepoint scores are associated with greater changes in trip length. In other words, these network design characteristics significantly predict the efficiency of the trips that remain feasible post-disaster. Finally, all else equal, longer commutes are more likely to be disconnected or rerouted. Urban planners can gradually shift the relative locations of homes and workplaces over time through rezoning (i.e., emphasizing accessibility over mobility) to bring them into closer proximity could be one path forward.

However, these regression models only provide global parameter estimates. This masks heterogeneity, which we unpack with the case studies to reveal that street network design does matter—but so do broader manifestations of the urban landscape and its topography. In the case of Des Moines versus Las Vegas and Phoenix, we see how design helps explain the difference in outcomes. In cities like Miami and Portland, good design still matters, but is only relevant if it is in an area that is otherwise sufficiently climate-resilient against extreme floods. For example, in urban planning practice, Portland is often recognized as an icon of good urban design and its values for the three key street network variables of interest are consistent with that profile. But the case study shows urban planners how good design alone cannot save you if you have other geographical vulnerabilities: Portland's hilly areas sprawling to the east and west of the Willamette River see local trips remain intact after other low-lying—yet dense and well-connected—street networks fail in the flood simulation. In an era of more extreme climate-driven disruptions to our cities, this demonstrates why good design matters, but so does building in a climate-resilient location. Similar takeaways apply to policymakers in cities like Los Angeles and San Francisco: a neighborhood's network design becomes irrelevant if it is entirely buried under earthquake rubble.

This study extends the literature by investigating empirical commutes and their local environs, rather than randomized trips or theoretical network performance as a whole. This is important for urban planners and policymakers because commutes present a unique equity challenge. The Covid-19 pandemic showed that, under duress, commutes can become discretionary trips for advantaged communities—who can shift to working from home as most creative work can occur remotely and flexibly—but are usually mandatory trips for disadvantaged communities, who must show up in-person and on-time for physical labor. In other words, commute vulnerability theoretically has greater ramifications for the poor than the wealthy. Maintaining these links to livelihoods is a key leverage point for urban planners seeking more just and sustainable cities. Furthermore, unlike other kinds of accessibility, one cannot substitute commutes. A person has one job and needs to maintain access to only that one. Conversely, if a food market becomes unreachable post-disruption, most people could substitute access to a different one elsewhere in the MSA. Jobs and commutes do not work that way, and this nonsubstitutability makes them more fragile to disruption.

In an era of climate change and social inequity, the sustainability and resilience of our urban transport infrastructure becomes ever more important to planning and policymaking. These infrastructure networks are vulnerable—to varying degrees—to different disruptions and disasters, but networks are expensive to redesign and redundancy is always expensive. This study demonstrates how good design can make networks more resilient—and in turn make commutes more secure—after a disruption, but it also reveals to planners how this interacts with urban geography and climate resilience more broadly to determine outcomes.

Conclusion

Commutes in the U.S. depend on the street networks that structure the human flows through the urban environment. Disruptions to this vital infrastructure can inflict widespread economic harm by disconnecting people from their livelihoods for extended periods of time, or making essential trips less efficient. Despite this importance, a comprehensive empirical understanding of U.S. commute vulnerability—and network design's role in it—has been lacking in the literature. This study addressed this gap through a set of large-scale simulations of U.S. commutes before and after different types of disaster events. It assessed the vulnerability of commutes to these disruptions and identified network design characteristics associated with vulnerability.

Our findings identified the importance of network connectedness, efficiency, and redundancy to the resilience and robustness of commute trips. Designing new and retrofitting old networks along these principles can help advance urban planning's societal goal of building resilient and sustainable cities. Planners need a strong evidence base for better evidence-informed planning, particularly to support key human livelihood processes—such as commutes—that rely on both natural and artificial elements of the urban environment.

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Data Management Plan

Products of Research

Datasets of OpenStreetMap street networks, Census Transportation Planning Products (CTPP) commuting flows, and Labor Employment and Housing Development (LEHD) employment centers are either collected or calculated for the purposes of this research. Simulations of network disruptions are performed on those datasets. Heterogeneous patterns of street networks under disruptions are presented. All the datasets mentioned are publicly available. The output datasets of our simulations will be provided below.

Data Format and Content

The datasets are presented in comma-separated value (CSV) spreadsheet formats. Access to all datasets is provided through the link below at Figshare. Due to their substantial size, it is recommended to download the datasets in the .zip format and perform operations on a local machine. Two datasets are shared: the node attribute and the origin-destination result data. The node attribute data encompasses the coordinates, network characteristics, and other pertinent information of nodes utilized in this research for each MSA. The origin-destination result comprises the trip-level simulation outcomes of the study.

Data Access and Sharing

The data that support the findings of this study are openly available in Figshare at http://doi.org/10.6084/m9.figshare.28736918.

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