SUPPLEMENT: Megaregional adaptation and recovery priorities preserve local resilience in the US Northeast rail corridor

1 S1: Results

Displacement plots were produced to visualize differences in total integrated local (R-L) and global (R-G) resilience produced by contrasting local (S-L) and global (S-G) prioritization strategies (Figure 1). This was done for each combination of node-level importance measure (DC, CC, δE BC, RWBC), simulation phase (failure and recovery), and RTN (each of fifteen urban, regional, and intercity systems).

In the recovery phase, δE and DC exhibited comparable performance with betweenness under S-G, with degree centrality offering a tradeoff of slightly greater R-L but lesser R-G relative to RWBC for urban and regional scales. In contrast to the competitive performance of degree centrality under S-G, under S-L it resulted in the lowest R-L of the five metrics considered across all scales. Furthermore, the uniform degree distribution of intercity rail caused DC to result in poor R-L and R-G regardless of strategy choice. Interpretation of other measures' results is included in the main text.

2 S2: Preprocessing of station ridership data

Rail transit networks included in this case study include 15 urban, regional, and intercity systems (Figure 2). From North to South, these include the MBTA subway (Boston), NYC Subway (New York), Port Authority Trans-Hudson (PATH, New York/New Jersey), SEPTA Metro (Philadelphia), MTA SubwayLink (SL) and Light RailLink (LRL) (Baltimore), and WMATA Metrorail (Washington). The Newark Light Rail and Hudson-Bergen Light Rail systems, Northern New Jersey's two URTS operated by New Jersey Transit (NJT), were excluded due to a lack of available ridership data. The NEC's 8 regional systems include the MBTA Commuter Rail, CTDOT CT Rail, MTA Metro-North Railroad (MNR), MTA Long Island Rail Road (LIRR), NJ Transit, SEPTA Regional Rail, MTA Maryland Area Rail Commuter (MARC), and Virginia Railway Express (VRE). The backbone of the NEC's passenger rail is Amtrak, the US national intercity passenger rail service. Amtrak extends across most regional hub cities and serves interchanges connected to all other RTNs in the corridor. Interchange stations were consolidated single nodes rather than being represented

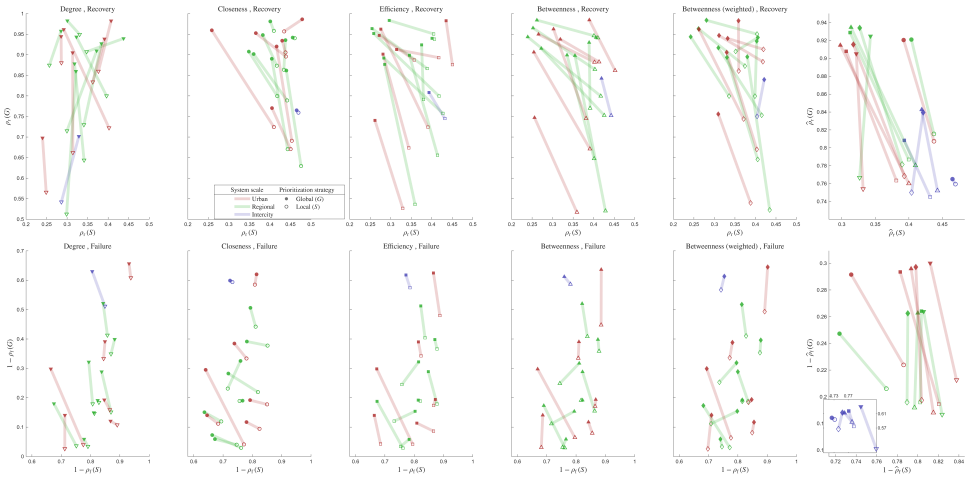


Fig. 1 Displacement plots of local (R-L) and global (R-G) resilience under local (S-L) and global (S-G) prioritization strategies. Each subplot shows the change in local and global resilience between S-G and S-L for each of 15 RTNs in the NEC megaregion. The top row shows recovery phase resilience, and the bottom row shows failure phase resilience (robustness). Plots for each importance measure are presented: degree (DC), closeness (CC), efficiency loss (δE), betweenness (BC), and ridership-weighted betweenness (RWBC). The rightmost plots show scale averages, aggregating results for URTS, RCR, and IPR. Marker symbols in the scale average plots correspond to the unique markers used for each importance measure. Symbol/measure pairs from left to right: nabla/DC, circle/CC, square/δE, pyramid/BC, diamond/RWBC.

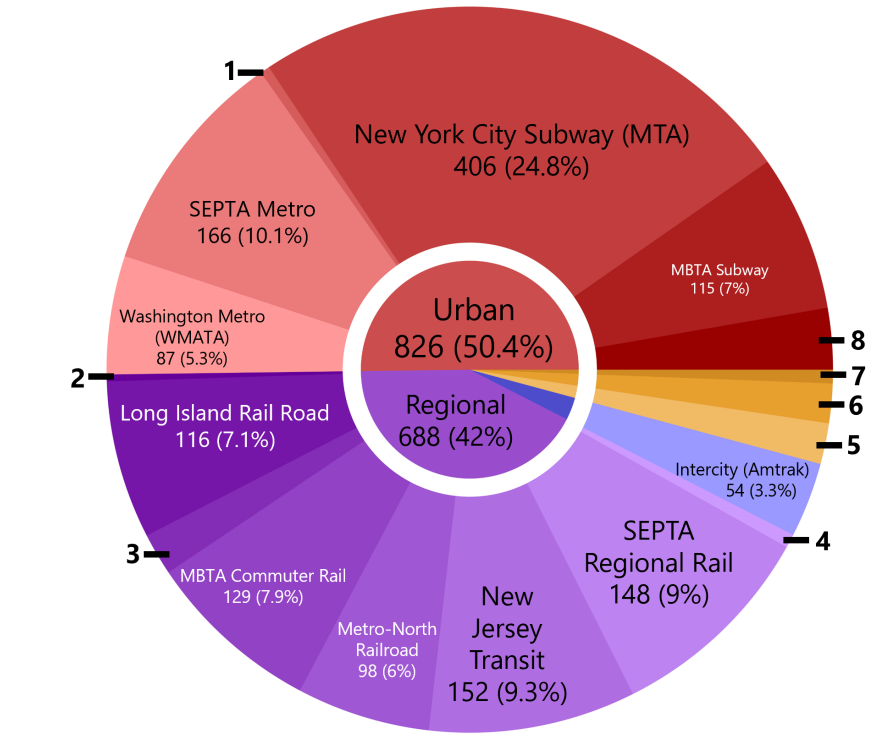
as multiple spatially-proximal connected nodes to better reflect realistic connectivity structure (Figure 4).

A review of available ridership data for each RTN was performed. The objective was to obtain station-disaggregated total annual ridership for each system for Fiscal Year (FY) 2019. Total annual unlinked trips was arrived at as the measure of choice due to being the lowest common denominator of available station-level ridership for the majority of RTNs in the NEC. FY2019 ridership was used to provide a relatively stable pre-COVID-19 pandemic baseline, as passenger rail systems in the US saw their utilization severely impacted by the pandemic. In the US in particular, RTN ridership has not yet recovered to projected pre-pandemic levels [1]. What follows is a detailed description of ridership data sources and formats for each RTN in the NEC case study, as well as correction methodology for interpolated or surrogate data in cases where the requested dataset was unavailable. Histograms showing the local and global distribution of station ridership are presented in Figure 3.

Bus rapid transit systems were outside the scope of this study, excluding the MBTA Silver Line (Boston, MA), RIPTA R-Line (Providence, RI), CT Fastrak (Hartford-New Britain, CT), MTA SBS (New York, NY), Hudson Link (Rockland & Westchester Counties, NY), and WMATA Metroway (Washington, D.C.).

2.1 Data: Regional Commuter Rail

The Northeast Rail Corridor is comprised of eight regional rail transit systems. The MBTA Commuter Rail serves Eastern New England, extending from Worcester,



1. Port Authority Trans-Hudson: 7 (0.4%)
2. CT Rail: 5 (0.3%)
3. Maryland Area Rail Commuter: 30 (1.8%)
4. Virginia Railway Express: 10 (0.6%)
5. Urban & Regional: 30 (1.8%)
6. Regional & Intercity: 32 (2%)
7. Urban, Regional, & Intercity: 12 (0.7%)
8. Baltimore Light Rail & Subway: 45 (2.7%)

Fig. 2 Station counts and percentage totals for each RTN contained within the Northeast Corridor megaregional network-of-networks. URTS, RCR, and IPR are shown in red, purple, and blue, respectively. Interchange stations are shown in orange.

Massachusetts in the West to Southern Rhode Island in the South and Rockport, Massachusetts in the North. Connecticut's CT Rail operates two commuter lines, serving the Connecticut River Valley between New Haven, CT and Springfield, MA on the Hartford Line and coastal Connecticut between Stamford and New London on the Shore Line East. New York City is the central hub of two regional rail systems: the Metro-North railroad provides service to the Hudson Valley and Western Connecticut, overlapping and sharing several stations with the Shore Line East as far west as New Haven, while Long Island is served by the Long Island Rail Road, extending from its City Terminal Zone in Manhattan, Brooklyn, and Queens in the West to Montauk and Greenport in the East. New Jersey Transit serves the state of New Jersey and connects with SEPTA's Regional Rail system serving greater Philadelphia. The Maryland Area Rail Commuter (MARC) covers the Baltimore and Washington, D.C. areas, and the Virginia Railway Express (VRE) extends from Washington, D.C. south to Richmond, Virginia.

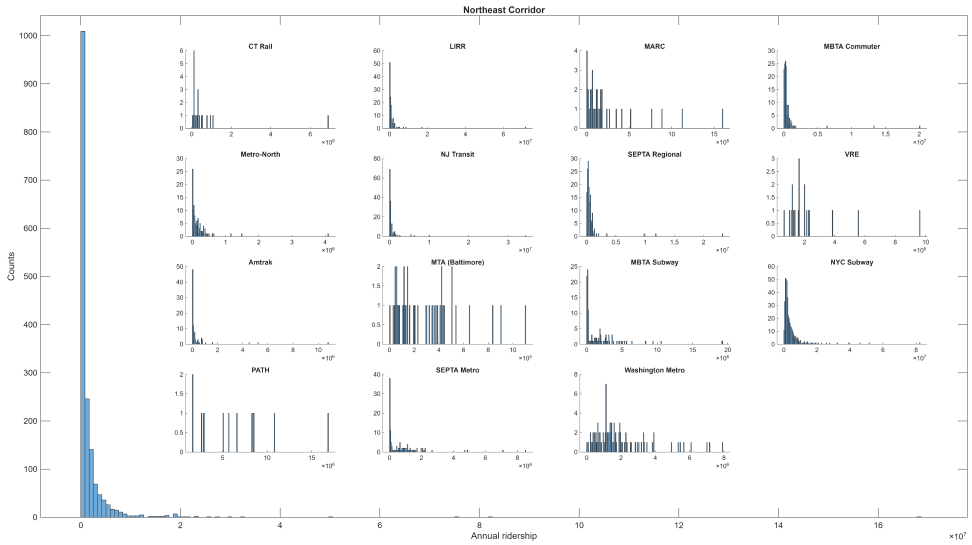


Fig. 3 Ridership (unlinked trip) distribution for individual rail transit networks (inset grid) and the Northeast Corridor Network-of-Networks (main, left). The station with the highest ridership in the NEC is New York Penn Station, the busiest passenger rail interchange in the Western Hemisphere [2], with estimated total FY2019 ridership of 168,519,579. This figure sums system totals from Amtrak (IPR), LIRR and NJT (RCR), and NYC Subway (URTS, 34th Street-Penn on the IRT Broadway-7th Ave line). Average FY2019 station ridership was $\bar{x}$ = 1,785,705 with a large standard deviation of σ_x = 5,900,427, and a median of $\tilde{x}$ =517,228

Virginia Railway Express: VRE ridership data was sourced from the system operator [3]. Data was available for the years 2017-2022. Data for 2019 was collected and used without further modification.

Maryland Area Rail Commuter: MARC FY2024 daily average ridership was sourced from the MDTA [4]. Values were adjusted to 2019 levels by multiplying by the ratio of system-wide FY2019 ridership to FY2024 ridership, for a constant value of 2.210 [5].

SEPTA Regional Rail: Data for 2019 SEPTA Regional rail ridership was provided by SEPTA via their online data portal [6]. Annual ridership was taken as the maximum value of the yearly total alights or egresses for each station.

New Jersey Transit: NJT data was sourced from the results of an OPRA request shared publicly [7]. For the River Line, the only station-level ridership data available online originated from a 2011 DVRPC report [8]. Data was extracted via manual estimation from Figure 4 of the report, the multiplied by the DVRPC-supplied ratio of NJ Transit ridership for 2019/2011 [9]. River Line ridership is the product of a one-day survey conducted on November 17, 2010. Caution should be exercised, as there is no guarantee that the survey is representative of statistical patterns averaged over longer timescales.

Metro-North Rail Road: There is no publicly accessible online dataset published by the MTA or any other state agency. Railroad.net forum user Brian Tschinkel hosts 2018 station-level ridership data purportedly acquired through a Freedom of Information Law request [10]. In lieu of official data, we use this dataset, and adjust

values to be in-line with 2019 ridership by multiplying with a constant taken as the ratio of FY2019 to FY2018 ridership, which fell to 98.9691% of FY2018 levels [11, 12].

Long Island Railroad: LIRR data for 2019 was sourced from maps created by the blog *The Long Island Rail Road Today* [13]. Ridership for Grand Central Madison Station reflects 2023 ridership, as Grand Central did not open as a LIRR stop until that year. The New York Governor's Office in a press release reported a 2023 total ridership of 17.1 million alights and egresses from Grand Central [14]. Dividing this number by two gives the ridership value used in this study.

Massachusetts Bay Transportation Authority Commuter Rail: Station-level ridership data was not available for 2019; the closest year with available data was 2018, sourced from the 2018 Commuter Rail Counts survey conducted by the Massachusetts Department of Transportation and the Central Transportation Planning Staff [15]. Raw data was received disaggregated by alights and egresses and inbound and outbound directions at the station level. For each station and direction, the maximum value of egresses and alights was taken. Inbound and outbound values are then summed together and multiplied by 365 to arrive at the final value. Ridership for stations that serve more than one commuter rail line was disaggregated by line; ridership for these stations was aggregated by simply summing values. Oak Grove Station was reopened as a commuter rail stop on the Haverhill Line in 2022 for the first time since 1985. Consequently, 2018 ridership data does not exist, and we could find no source for commuter rail ridership since 2022. We chose to address the missing data by an unweighted interpolation– the mean– of 2018 ridership values of its neighboring stations, Wyoming Hill (89, 790) and Malden Center (79, 205), giving Oak Grove a "retroactive" 2018 ridership of 84, 497.5. Spring 2018 station-level ridership was adjusted to 2019 values by multiplying each Spring 2018 value by the average system-level monthly mean ridership for March, April, and May 2018 divided by the system-level monthly mean ridership for all months of 2019, yielding a constant of 1.000750744 [16].

Connecticut Rail: No station-level ridership data for Connecticut's commuter rail system was located for any time period other than for the Shore Line East between New London and New Haven. Line-level ridership data was available for 2019 for the Hartford Line, with a total annual ridership of 731, 239 [17]. Every CT Rail station on the Hartford Line also serves as an intercity Amtrak station, for which 2019 station-level ridership was available. To distribute total line ridership to each station, we allocated ridership proportional to the Amtrak ridership at each station, making the assumption that intercity ridership will serve as an adequate proxy for regional ridership. Each station i was allocated Hartford Line ridership r_i^{H} using Amtrak ridership r_i^{A} as shown in Equation 1:

$$r_i^{\mathrm{H}} = r_{\mathrm{tot}}^{\mathrm{H}} \frac{r_i^{\mathrm{A}}}{\sum_{i \in N} r_i^{\mathrm{A}}} \tag{1}$$

where $r_{\mathrm{tot}}^{\mathrm{H}}$ is the line-total annual ridership for the Hartford Line and $\sum_{i \in N} r_i^{\mathrm{A}}$ is the sum of ridership for all Amtrak stops that share a station with the Hartford Line. Shore Line East station-level ridership data for New London-New Haven reported total alights and egresses for each station during 2019 [18]. Final ridership values were

arrived at by dividing raw values by 2. For stations from New Haven to Stamford, a similar approach was taken to that used for the Hartford Line. Because not every station (West Haven, Milford, Stratford, Bridgeport, and Stamford) shares a station with intercity services, we chose to allocate total ridership based on Metro-North Railroad ridership, again assuming that CT Rail ridership is roughly proportional with Metro-North ridership.

CT Rail stops served by recently suspended services were included as a member of the system. These include Stamford through service suspended during the COVID-19 pandemic and restored in October 2024, and South Norwalk Station, for which post-pandemic service did not return.

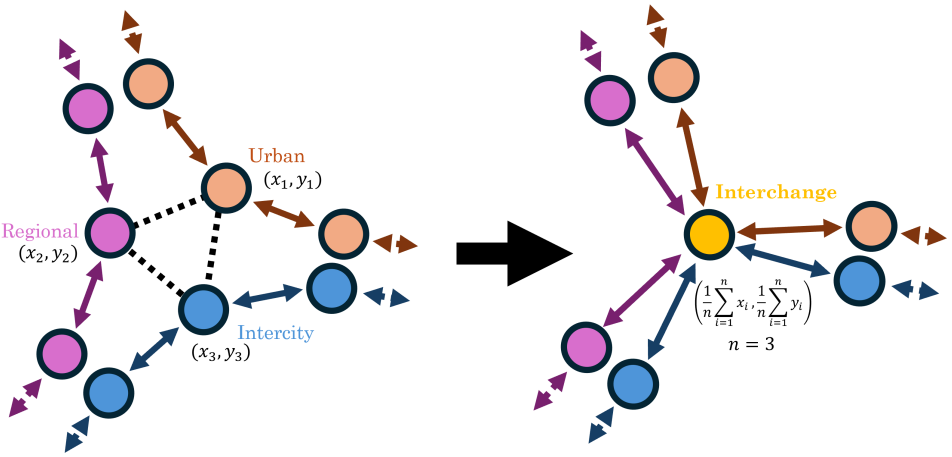


Fig. 4 Schematic for simplification of interchanges and station complexes into single nodes serving multiple RTNs. When the individual RTNs served by an interchange report slightly different locations, the geometric midpoint is calculated and used as the coordinates for the condensed interchange node.

2.2 Data: Urban Rapid Transit Systems

MDTA SubwayLink and Light RailLink: Baltimore URTS ridership data for the year 2024 was retrieved from the Maryland Transit Authority [19, 20]. Data was adjusted to 2019 levels by multiplying by the ratio of average monthly system-wide 2019 ridership to average monthly 2024 ridership [5].

SEPTA Metro: Publicly available ridership data for the SEPTA Metro system was scattered and disjoint. The Market/Frankford Line, now the L, and the Broad Street Line, now the B, only had station-level ridership available for FY 2017 [21]. Data was adjusted to 2019 levels by multiplying by the ratio of total SEPTA system ridership in 2019 to 2017, which saw a decline to approximately 95.00% of 2017 levels [22]. The Norristown High-Speed Line (now M1, M2) and Route 13 (T3), 15 (G1), 101 (D1), and 102 (D2) Trolleys were available seasonally for 2024-2025, but not pre-pandemic [23, 24]. As of July 2025, SEPTA reports Metro ridership recovery to 77% of 2019 pre-pandemic levels. Accordingly, ridership values were adjusted by multiplying

by 100/77 = 1.29870 [25]. For our purposes, the NJT River Line and PATCO were considered as part of Pennsylvania's transit systems.

Port Authority Trans-Hudson: PATH ridership data was taken from the port authority's monthly ridership report for year end 2019 [26].

Washington Metropolitan Area Transit Authority: WMATA Washington Metro average weekday and weekend ridership for FY2019 is published online by the system operator [27]. Data was published as average weekday and weekend boardings and adjusted to total annual ridership. For the Innovation Center, Dulles International Airport, Loudon Gateway, Ashburn, and Reston Town Center DC Metro Stations, 2023 ridership data was used, as these stations opened on November 15, 2022.

New York City Subway: FY2019 ridership data for the New York City Subway is published online by the New York MTA, and was used unmodified [28].

Massachusetts Bay Transportation Authority Subway: Due to data availability limitations, the data for the MBTA Subway reflects only the Fall of 2019, and corresponds to total egresses at each station [29]. Station-level ridership for the Mattapan trolley, a surface trolley service extending from the southern terminus of the red line, was not included with the dataset for the rest of the system. Station-level ridership for the Mattapan trolley was instead sourced from published material corresponding to a June 2023 public meeting on the topic of Mattapan trolley service improvement [30]. Ridership was adjusted to 2019 levels by multiplying Fall 2018 ridership by the ratio of average system-wide ridership for FY2019 to average system-wide ridership for Fall 2018.

2.3 Data: Intercity Passenger Rail

The backbone of the Northeast corridor providing intercity rail service, connection to other US regions, and connections that fill the gaps between commuter services is Amtrak, formally the National Railroad Passenger Corporation.

Amtrak: the US Bureau of Transportation Statistics publishes total annual ridership for all stations operated by Amtrak for all recent years, including FY2019 [31]. IPR ridership was used in its raw form without further pre-processing.

Table 1: Ridership data (unlinked trips) for each rail transit network comprising the NEC. Information includes data source, data collection period, units of the quantity reported, and any adjustments made during pre-processing. FY2019 data was selected as a stable baseline for this study. For cases in which 2019 data was unavailable, data was retrieved from proximal time periods for which it was. In most cases, adjustments were made by calculating the ratio of total system ridership for FY2019 relative to the available data period, then multiplying raw ridership values by the resulting factor.

System	Source	Period	Format	Adjustment	Adj. Factor
MBTA Subway	Operator[29]	Fall 2018	total on/off, in/out	FY19/Fall18	0.956

System	Source	Period	Format	Adjustment	Adj. Factor
MBTA Subway (Mattapan Trolley)	Public meeting document[30]	Fall 2018	average wkday	FY19/Fall19	0.956
NYC Subway	Operator[28]	FY2019	total ann.		
PATH	Operator[26]	FY2019	total ann.		
SEPTA Metro (L, B)	Operator[21]	FY2017	avg. wkday /Sat/Sun	FY19/FY17	0.950
SEPTA Metro (M, T, G, D)	Operator[22, 25]	Seasonal 2024-2025	total ann.	Reported pre-/post-COVID-19 levels	1.299
Baltimore SubwayLink	Operator[5, 20]	FY2024	avg. ann. wkday/ wkend, on/off	FY19/FY24 Monthly average	1.474
Baltimore Light RailLink	Operator[5, 19]	FY2024	avg. ann. wkday/ wkend, on/off	FY19/FY24	1.347
Washington Metro	Operator[27]	FY2019	avg. wkday /wkend on		
Virginia Railway Express	Operator[3]	FY2019	total ann. on/off, in/out		
Maryland Area Rail Commuter	Operator[4, 5]	FY2024	avg. ann. wkday/ wkend on/off	FY19/FY24	2.210
SEPTA Regional Rail	Operator[6]	FY2019	total ann. on/off		
New Jersey Transit	OPRA request[32]	FY2019	avg. wkday on/off		
Metro-North Railroad	FOIL request[10]	FY2018	avg. wkday /wkend on/off	FY19/FY18	0.990
Long Island Rail Road	Third-party[13]	FY2019	total ann. on/off		
CT Rail (Hartford Line)	Public agency[17]	FY2019	total ann. system-wide	Proportional to Amtrak	
CT Rail (Shore Line East)	Public solicitation[18]	FY2019	avg. wkday /wkend on/off		

System	Source	Period	Format	Adjustment	Adj. Factor
MBTA Commuter Rail	Public agency[15, 16]	Spring 2018	total on/off, in/out	FY19/Sp18	1.001
Amtrak	Public agency[31]	FY2019	total ann.		

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