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BRIEF REPORT

Road-Closure Stress Testing of Essential-Service Accessibility in Yemen

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Abstract

Road disruption can change access to basic services even when the services themselves remain in place. This study develops a national network stress test for Yemen using OpenStreetMap road extract and WorldPop constrained population surface. Demand is represented by 8,460 population-weighted grid cells covering 41.18 million people and linked to mapped markets, health facilities, and fuel stations. The study then evaluates five stylized closure mechanisms at 1%, 5%, 10%, and 20% of simplified physical road links, including random removal, spatially clustered removal, major-road targeting, access-betweenness targeting, and exact-bridge targeting. At 1% random removal, the mean newly disconnected population share across services is 1.12%, indicating a shallow low-intensity response. The most disruptive mechanism depends on closure intensity. Exact bridges produce the largest disconnection at 1% closure (15.65% across services), access-betweenness targeting at 5% (35.28%), and major-road targeting at 10% and 20% (49.65% and 65.04%). Among people who remain connected, rerouting is highest under major-road targeting at 1% and 5%. At higher intensities, connected-only delay becomes non-monotonic because disconnected users no longer remain in that distribution. Spatial closures look modest in national averages but impose severe local losses. At 1% closure, 2.01% of the national population is newly disconnected, compared with 59.64% of the population within 25 km of the closure center and 93.95% within the realized closure footprint. These findings show that national averages should be complemented by local exposure measures when assessing road-network vulnerability and prioritizing access-sensitive recovery.

Keywords Yemen · Accessibility · Road-network vulnerability · OpenStreetMap · WorldPop · Service access · Percolation · Spatial disruption

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Introduction

Access to roads conditions whether people can reach food markets, health care, fuel, employment, and humanitarian assistance. In Yemen, difficult terrain, prolonged institutional fragmentation, damaged infrastructure, checkpoints, and uneven service provision shape everyday movement (Coombs & Salah, 2023; Schouten et al., 2024, 2026; United Nations Office for the Coordination of Humanitarian Affairs [OCHA], 2025). A limited disruption may therefore have effects well beyond the link that becomes unavailable. Against this background, this study asks how access to mapped essential services changes when different types and proportions of road links are removed from the network.

Observed roadblocks and stylized link-removal scenarios are not equivalent. In conflict-affected settings, checkpoints and roadblocks can regulate taxation, authority, and movement as well as physical passage (Schouten et al., 2024, 2026). Reports on Yemen document damaged corridors, bridge failures, movement restrictions, and rising transport burdens (Coombs & Salah, 2023). The 2025 humanitarian plan further documents continuing operational constraints and barriers affecting access to essential assistance and services (OCHA, 2025). However, the public sources reviewed for this study do not provide a consistently timed and geolocated national inventory of road closures. The analysis therefore does not estimate a causal conflict effect. It identifies how alternative patterns of link loss redistribute access burdens across the population and shows which conclusions depend on modelling choices.

Accessibility provides the conceptual basis for this analysis. It concerns the ease with which people or places can reach opportunities, services, and activities under time, cost, and institutional constraints (Geurs & van Wee, 2004; Hansen, 1959). Road-vulnerability studies apply this idea to disrupted networks by measuring changes in travel cost, reachability, and exposure after links are removed (Berdica, 2002; Jenelius et al., 2006; Mattsson & Jenelius, 2015; Taylor et al., 2006). Percolation analysis complements these measures by tracing the loss of connectivity under progressive random or targeted removal (Callaway et al., 2000; Duan & Lu, 2014). This study combines these approaches to compare localized interruption, diffuse random failure, major-road loss, and removal of structurally important links.

It addresses four research questions (RQs). RQ1 asks what baseline population-weighted access to mapped markets, health facilities, and fuel stations is. RQ2 analyses how random, spatial, major-road, access-betweenness, and bridge-based closures change rerouting and disconnection at 1%, 5%, 10%, and 20% link removal. RQ3 asks how much more severe spatial closures are for nearby populations than national averages suggest. RQ4 addresses the sensitivity of the results to the population layer, disconnection penalties, strategic-ranking weights, and the use of cumulative opportunities rather than nearest-service access.

Data and Methods

This section sets out the choices that define the stress test. It begins with the accessibility concept, then describes the road, service, and population data before explaining the closure mechanisms, outcome measures, and uncertainty analysis.

Accessibility Concept and Scope

The study uses a place-based accessibility measure weighted by population. Service opportunities are represented by mapped locations, and access is calculated from residential demand cells to those locations. Each demand cell carries a gridded population count, so national averages reflect where people live rather than treating places equally. A fully person-based measure would instead represent individual schedules, activity sequences, mobility resources, trip chaining, temporal constraints, household responsibilities, and preferences. Such measures can reveal inequalities hidden by area averages, but they require travel diaries, mobility traces, or synthetic populations that are unavailable nationally for Yemen (Geurs & van Wee, 2004). Moreover, collecting or reusing individual mobility traces in a conflict-affected humanitarian setting creates data-protection and potential-harm risks that require explicit safeguards (Inter-Agency Standing Committee [IASC], 2023).

A place-based design fits the purpose of this study because it compares alternative network states at national scale rather than predicts realized individual trips. It can be implemented transparently with open spatial data and updated when roads or service locations change. These advantages do not remove its limitations. A mapped facility may be closed, intermittently operational, unaffordable, unsuitable for a particular need, or inaccessible for reasons outside the road graph. Access to the nearest mapped service is also a narrow outcome. The study therefore adds a cumulative-opportunity check that counts mapped services reachable within 30 and 60 network minutes for a population-weighted sample of demand locations.

OpenStreetMap Road and Service Data

The road and service layers are drawn from the Yemen OpenStreetMap PBF extract yemen-260,725.osm.pbf, created by OpenStreetMap contributors and distributed by Geofabrik GmbH under the Open Database Licence (OpenStreetMap contributors, 2026). See Fig. 1 for a map of Yemen and Table 1 for the research design overview. Its header records an osmosis replication timestamp of July 25, 2026 at 20:21:51 UTC and a Geofabrik Yemen update-stream base URL. OpenStreetMap is a volunteered geographic information system. Contributors create nodes, ways, and relations and describe them through key-value tags. A road way is an ordered sequence of nodes, while tags such as highway=primary, maxspeed = 80, bridge = yes, or amenity=fuel record its class or attributes. Individual volunteers, mapping communities, public

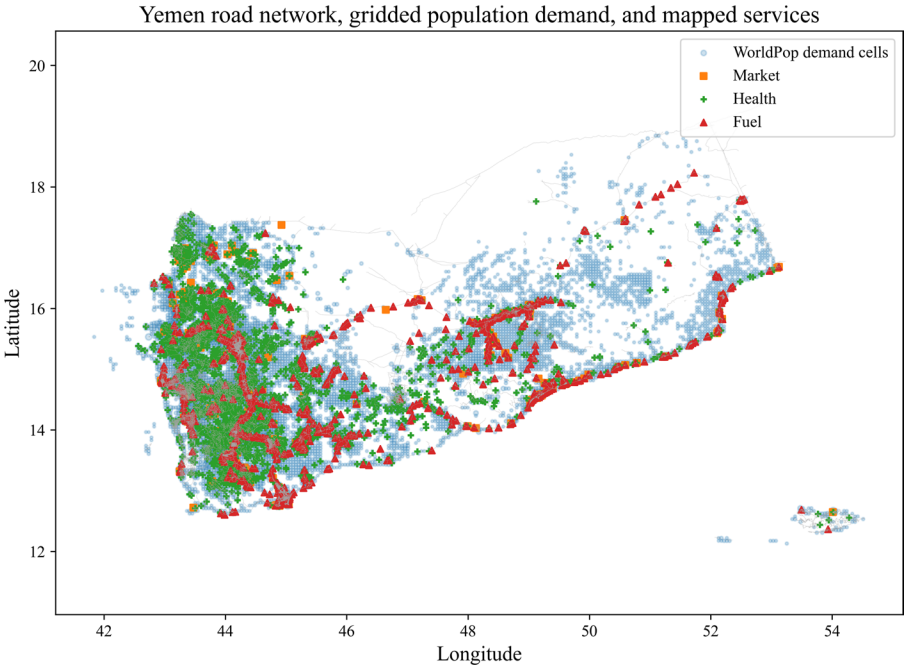

Fig. 1 Yemen road network, population demand, and mapped service locations. (Road and service data © OpenStreetMap contributors, available under the Open Database Licence, extract processed and distributed by Geofabrik GmbH. Population data © WorldPop, licensed under CC BY 4.0.)

and private organizations, imports, and humanitarian mapping campaigns can all make edits. The resulting data are therefore produced through a decentralized process rather than a single national survey.

This decentralized production model gives OpenStreetMap broad coverage and reproducibility, but not uniform quality. Global assessments report substantial OpenStreetMap road coverage while documenting considerable geographic variation in completeness (Barrington-Leigh & Millard-Ball, 2017). Comparative assessments also identify variation in completeness and positional accuracy relative to authoritative mapping data (Haklay, 2010). Possible alternatives include official road-agency or cadastral databases, commercial navigation networks, satellite-derived road products, and humanitarian logistics or access-constraint datasets. Official and commercial sources may contain more standardized attributes, and satellite products may identify unmapped roads. They may also be unavailable, costly, difficult to reproduce, or lack routable topology and service tags.

This study retained drivable road classes and excluded explicitly non-motorized classes. The parser extracted 2,492,128 raw nodes and 2,577,478 node-to-node segments. Many of these segments merely connect intermediate geometry points, so they are not meaningful closure units. After simplification, the graph contains 241,016 intersection or endpoint nodes and 323,548 undirected physical links representing 101,515 km of roads. All closure percentages refer to these simplified links. The graph has 517 connected components. Its largest component contains 94.91% of

Table 1 Analytical inputs and design choices

Component	Specification	Purpose
Road extract	OpenStreetMap Yemen PBF, snapshot 25 July 2026	National drivable network and mapped services
Raw network	2,492,128 nodes; 2,577,478 node-to-node segments	Intermediate geometry retained only during parsing
Simplified network	241,016 nodes; 323,548 physical links; 101,515 km	Closure denominator and routing graph
Population demand	WorldPop 2025 constrained raster aggregated to 8,460 ~ 5-km cells	41.18 million represented people
Services	1,688 markets; 3,218 health; 1,178 fuel	Mapped OSM features, not verified operation
Closure levels	1%, 5%, 10%, and 20% of simplified links	Nested within each scenario realization
Stochastic replication	100 replicates for random, spatial, and major-road scenarios	95% percentile bootstrap intervals, 2,000 draws
Deterministic scenarios	Access-betweenness and exact-bridge targeting	No stochastic confidence interval
Primary delay outcome	Connected-only rerouting minutes	Disconnection reported separately
Access-loss thresholds	10, 30, and 60 added minutes or disconnection	Multiple thresholds avoid dependence on one cutoff

simplified nodes and 96.55% of WorldPop demand weight. The study treats links as undirected to prevent directional-search artifacts in the passability stress test, while recognizing that this choice omits one-way and turn restrictions.

Link travel time is calculated from physical-link length and speed. Where OpenStreetMap provides a parseable `maxspeed` value, the value is converted to kilometres per hour. Values expressed in miles per hour are converted using 1 mile = 1.609344 km. Empty values and nonnumeric designations such as `signals`, `walk`, `variable`, `national`, `urban`, and `rural` are treated as unavailable. Parsed speeds at or below zero or above 180 km/h are also rejected. Only 1.60% of simplified physical links contain a usable observed `maxspeed`, so most links use road-class defaults: 90 km/h for motorway, 60 for motorway_link, 80 for trunk, 50 for trunk_link, 60 for primary, 45 for primary_link, 50 for secondary, 40 for secondary_link, 40 for tertiary, 35 for tertiary_link, 35 for unclassified, 30 for residential, 15 for living_street, 20 for service, 15 for track, and 30 km/h for road or an otherwise unmatched class. Travel times should therefore be interpreted primarily as internally consistent network impedances for comparing network states, not as predictions of realized driving time.

The physical-link graph is constructed by contracting chains of intermediate OpenStreetMap geometry nodes. A node is retained as an endpoint when its undirected degree differs from two or when the attributes of its two incident road segments differ. To avoid eliminating an entire closed ring in which every node has degree two, at least one node is retained in any such component. Consecutive segments between

retained endpoints are then combined into one physical link. This preserves intersections, terminal endpoints, and changes in road attributes while removing shape points that have no routing decision function. Closure percentages are subsequently applied to these simplified physical links rather than to raw OpenStreetMap node-to-node segments. The resulting graph contains 241,016 nodes and 323,548 physical links representing approximately 101,515 km of roads.

Service locations are selected through explicit OpenStreetMap tag queries. Markets comprise amenity=marketplace and the shop values supermarket, convenience, general, and greengrocer. Health features comprise the amenity values hospital, clinic, and doctors and the healthcare values hospital, clinic, doctor, centre, and center. Fuel services use amenity=fuel. Polygon and multipolygon features are converted to representative points for network matching. The inventory contains 1,688 market features, 3,218 health features, and 1,178 fuel features, matched to 1,497, 2,825, and 1,080 unique graph nodes, respectively. These counts describe mapped features, not verified operational facilities.

Gridded Population Demand

Population demand comes from the 2025 constrained WorldPop R2025A v1 surface at approximately 100-m resolution (Bondarenko et al., 2025). WorldPop uses a random-forest dasymetric framework with remotely sensed and ancillary covariates to disaggregate census or projection totals (Stevens et al., 2015; Tatem, 2017). This study aggregates the raster count-preservingly to approximately 5-km cells so that repeated national routing is computationally feasible. All 8,460 positive cells are retained. The cells represent 41,179,068 people.

The OpenStreetMap settlement layer contains 76,889 named settlements, of which 46,013, or 59.84%, have a valid population tag. The raw total recorded in those tags is 14.22 million. Assigning a weight of one to every untagged settlement and then applying a uniform national scaling factor cannot recover the missing rural and peri-urban distribution. The validation results are correspondingly weak. The Spearman correlation between log OSM population weights and WorldPop population aggregated around settlements is 0.061 for all settlements and 0.075 among settlements with valid population tags. These correlations support the use of WorldPop as the main demand layer.

Closure Mechanisms

The study models five patterns of link loss. In the random scenario, simplified links receive a uniform random ordering and the first 1%, 5%, 10%, or 20% are removed. The ordering is nested within each replicate. The spatial scenario chooses a population-weighted random center and removes links by projected midpoint distance, producing a compact footprint. The major-road scenario first identifies motorway, motorway_link, trunk, trunk_link, primary, primary_link, secondary, and secondary_link physical links. Within each replicate, these links are randomly ordered, as are all remaining links, and the major-road ordering is placed first. Closure quotas therefore remove major-road links before drawing from the remainder of the network. If the

requested quota exceeds the number of links in these classes, non-major links fill the balance. The same replicate-specific ordering is used at 1%, 5%, 10%, and 20%, so closure sets are nested within each realization.

To make strategic targeting transparent, the study uses sampled access betweenness and exact graph bridges rather than a composite based on road class, length, travel time, and endpoint degree. Sampled access betweenness records how often a link lies on sampled shortest paths between population demand nodes and service nodes, after which each link receives a percentile-normalized score. The access-betweenness calculation uses 60 population-demand source nodes and 60 service target nodes. Demand sources are sampled without replacement from unique road-network nodes, with selection probabilities proportional to their aggregated WorldPop population weights. Service targets are sampled without replacement from the pooled set of unique mapped market, health, and fuel service nodes that belong to the graph. The source and target samples are generated with deterministic seeds derived from the master seed of 260725 and are therefore held fixed throughout the strategic-ranking comparisons. Edge betweenness is then calculated for this source-target subset using travel time as the edge weight and NetworkX's normalized subset edge-betweenness calculation.

For physical link (i), the baseline strategic score is (S_i=0.80B_i+0.20G_i), where (B_i) is the percentile rank of sampled access betweenness and (G_i) equals one when the link is an exact graph bridge and zero otherwise. Links are sorted first by this composite score, then by raw access betweenness, with the stable physical-link identifier used as the final deterministic tie-breaker. Exact graph bridges are identified on the simplified undirected network using the graph-theoretic bridge algorithm. Removing any such edge increases the number of connected components. In the exact-bridge scenario, all exact bridges are placed before non-bridges. Bridges are ordered internally by sampled raw access betweenness, followed by road-class score and stable physical-link identifier as tie-breakers. Once all exact bridges have been exhausted, non-bridge links fill any remaining closure quota using the same ordering variables. The scenario therefore tests bridge-first disruption without assuming that every requested closure share consists exclusively of graph bridges.

The composite score has a Spearman correlation of 0.472 with raw sampled access betweenness. At the 1% and 5% thresholds, the selected links overlap the pure-betweenness ranking by Jaccard coefficients of 0.878 and 0.731. At larger quotas, exact bridges make up more of the composite selection, so overlap with pure betweenness declines. The study tests 60/40, 80/20, and 100/0 betweenness/bridge weights and reports both rank correlations and changes in outcomes.

Accessibility Outcomes

For each demand cell and service type, baseline access is the shortest travel time to any mapped service node on the intact graph. Scenario access is recalculated after the selected physical links are removed. Demand-service pairs that are unreachable at baseline are reported separately and excluded from the denominator for closure-induced disconnection. For pairs that remain connected, rerouting delay is the difference between scenario and baseline travel time. The study reports the popula-

tion-weighted mean over the full population, with disconnected pairs contributing zero to the rerouting component, and the mean among people who remain connected. The second measure most directly captures detour burden.

New disconnection is the population share that can reach a service at baseline but cannot reach one after closure. Composite access-loss shares include people who are newly disconnected or face at least 10, 30, or 60 additional minutes. Population-weighted person-hours per trip are the sum of population weight multiplied by connected-pair rerouting minutes, divided by 60. The study audits this identity for every output row. The main analysis neither assigns a finite time penalty to disconnection nor monetizes person-hours. A separate sensitivity exercise applies penalties of 60, 120, 240, and 480 min to show how much a penalized total depends on the selected constant.

Uncertainty and Robustness

The study estimates uncertainty separately for stochastic and deterministic mechanisms. For random, spatial, and major-road closures, 100 independently seeded scenario realizations provide the stochastic sampling distribution for each service, closure level, demand layer, and outcome. The reported 95% intervals are percentile bootstrap confidence intervals for the mean simulation outcome. For each cell, 2,000 bootstrap samples are drawn with replacement from the replicate-level estimates, with each bootstrap sample containing the same number of observations as the original replicate set. The mean is calculated for every bootstrap sample, and its 2.5th and 97.5th percentiles define the reported interval. These intervals therefore quantify Monte Carlo uncertainty in the estimated mean across simulated closure realizations. They are conditional on the road network, WorldPop surface, mapped service inventory, speed assumptions, and other model inputs being fixed. They do not include measurement uncertainty in OpenStreetMap, WorldPop, or facility operating status. Access-betweenness and bridge scenarios are deterministic, so the study reports point estimates and examines uncertainty through alternative ranking definitions and weights. Bootstrap rank probabilities measure how often a mechanism or service has the highest new-disconnection value within a closure intensity. Ties are counted as co-highest.

Six further checks examine whether the findings depend on implementation choices. A random-removal percolation curve traces new disconnection from 0% to 20% in one-percentage-point increments across ten replicates. The study compares WorldPop estimates with the OSM settlement-weight layer, separates finite disconnection penalties from rerouting, and varies the strategic composite across three betweenness/bridge weights. The cumulative-opportunity robustness check counts mapped services reachable within 30 and 60 network minutes. To keep repeated national single-source routing computationally tractable, 150 unique demand nodes are sampled without replacement with probabilities proportional to their WorldPop population weights, using a deterministic seed derived from the master seed of 260725. The same 150 nodes and their population weights are retained across the intact baseline and every closure scenario. The comparison uses 10% closure. For the stochastic random, spatial, and major-road mechanisms, the closure set is the first seeded realization (replicate 0) generated under the same scenario algorithm used in

the main analysis. Access-betweenness and exact-bridge scenarios use their deterministic rankings. The resulting check is therefore a fixed-sample sensitivity analysis rather than an additional 100-replicate experiment. Finally, an arithmetic and routing audit checks the person-hour identity and counts negative raw travel-time changes. The count is zero across all scenario results.

Results

The findings first describe access on the intact network, then compare closure mechanisms and service types, and finally examine the difference between national averages and the burden experienced near spatial closures.

Baseline Network and Service Accessibility

Baseline access varies markedly across service types (see Table 2). Among people connected to the intact graph, mean travel time is 25.24 min to a market, 18.57 min to fuel, and 5.70 min to a mapped health feature. The lower medians of 13.90, 8.29, and 3.42 min indicate right-skewed distributions in which a smaller population faces much longer journeys. The 90th percentile is 62.02 min for markets, 51.02 min for fuel, and 12.94 min for health. Within 30 min, 68.67% of the represented population can reach a market, 77.26% can reach fuel, and 98.20% can reach a mapped health feature.

At baseline, 1.70% of the population is unreachable from markets, 1.52% from fuel, and 0.66% from health. The study does not count these groups as newly disconnected in any closure scenario. The shorter travel times to health features do not imply that functioning health care is universally nearby. The OSM layer contains 3,218 health features, nearly twice the number of markets and almost three times the number of fuel stations, and spacing differs across the three inventories. The mean snapping distance is also greater for health features, at 1.30 km, than for markets at 0.15 km or fuel at 0.53 km. This difference suggests greater uncertainty in how some health features are connected to the routable graph, although it does not by itself establish that their mapped coordinates are inaccurate.

Effects by Closure Mechanism and Intensity

Limited random removal does not produce an immediate national collapse. At 1% random removal, mean connected-only rerouting across services is 0.87 min, and

Table 2 Population-weighted baseline access to the nearest mapped service

Service	Baseline reachable	Mean min	Median min	P90 min	Within 30 min	Within 60 min
Markets	98.30%	25.24	13.90	62.02	68.67%	87.73%
Health	99.34%	5.70	3.42	12.94	98.20%	99.08%
Fuel	98.48%	18.57	8.29	51.02	77.26%	91.35%

Note. Travel-time summaries apply to baseline-reachable population. Within-threshold shares use the full represented population

1.12% of the population becomes newly disconnected (see Table 3). The broader access-loss measure, which includes people who are either newly disconnected or remain connected but experience at least 10 additional minutes of travel, reaches 3.22%. The independent percolation curve shows the same shallow response at the low end (see Figs. 2 and 3).

The ranking of mechanisms changes with both intensity and outcome. At 1% closure, exact bridges produce the greatest disconnection, 15.65% across services, although connected-only rerouting among survivors is only 0.36 min. This pattern is characteristic of cut links. Some users lose reachability, while many who remain connected require little or no detour. Access-betweenness targeting disconnects 7.32% at 1% closure, and major-road targeting disconnects 4.26%. The latter nevertheless produces the largest connected-only rerouting, 5.91 min. No mechanism is therefore most damaging on every measure.

At 5% closure, access-betweenness targeting has the highest mean new-disconnection share, 35.28%, followed by major-road targeting at 28.44% and exact-bridge targeting at 28.32%. Major-road targeting produces the largest connected-only rerouting, 13.85 min, compared with 6.94 min for access-betweenness targeting. At 10% and 20%, major-road targeting has the highest new-disconnection shares, 49.65% and 65.04%. Access-betweenness targeting reaches 47.07% and 57.80%. Random

Table 3 Mean effects across market, health, and fuel access at all closure levels

Mechanism	Closed links	Connected-only added min	Newly disconnected	Loss >= 10 min or disconnected	Rerouting person-hours/trip (m)
Random	1%	0.87	1.12%	3.22%	0.582
Random	5%	4.58	6.98%	15.75%	2.837
Random	10%	7.65	16.93%	28.37%	4.116
Random	20%	6.59	40.59%	48.26%	2.377
Spatially clustered	1%	0.08	2.01%	2.19%	0.052
Spatially clustered	5%	0.18	7.10%	7.44%	0.114
Spatially clustered	10%	0.18	12.33%	12.66%	0.104
Spatially clustered	20%	0.33	23.19%	23.69%	0.168
Major-road targeted	1%	5.91	4.26%	15.20%	3.769
Major-road targeted	5%	13.85	28.44%	42.64%	6.126
Major-road targeted	10%	13.46	49.65%	60.33%	3.901
Major-road targeted	20%	9.20	65.04%	70.85%	1.768
Access-betweenness	1%	2.11	7.32%	11.77%	1.305
Access-betweenness	5%	6.94	35.28%	43.07%	2.756
Access-betweenness	10%	6.54	47.07%	53.39%	2.077
Access-betweenness	20%	6.21	57.80%	62.92%	1.619
Exact-bridge	1%	0.36	15.65%	16.35%	0.201
Exact-bridge	5%	0.56	28.32%	29.45%	0.266
Exact-bridge	10%	0.83	35.69%	36.87%	0.354
Exact-bridge	20%	3.33	45.97%	50.15%	1.173

Note. Values average the three service-specific population-weighted outcomes. The full service-specific table with 95% intervals is provided in Appendix 3. Deterministic scenarios do not have stochastic confidence intervals

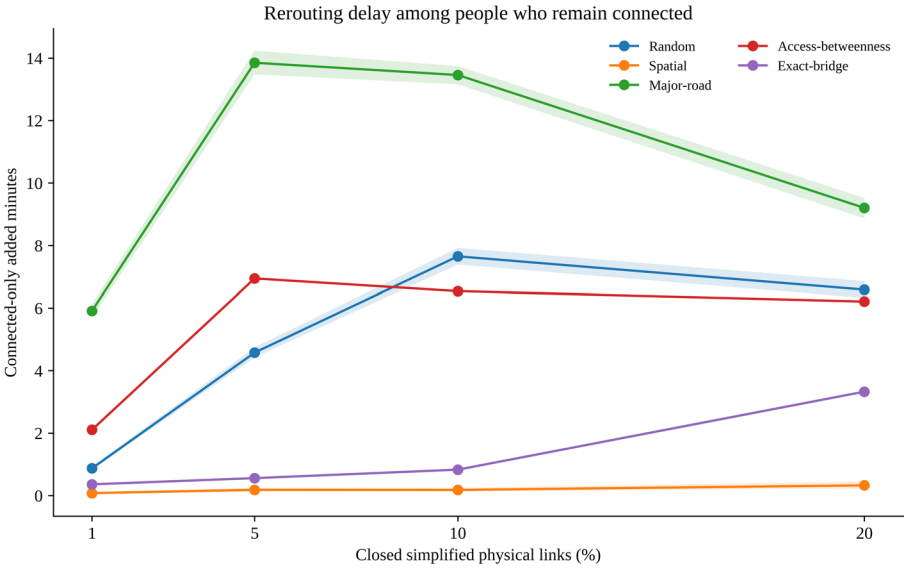

Fig. 2 Connected-only rerouting delay by closure mechanism. Lines average the three service categories. Shaded bands summarize the service-averaged 95% replicate intervals for stochastic scenarios. Deterministic mechanisms are shown without bands

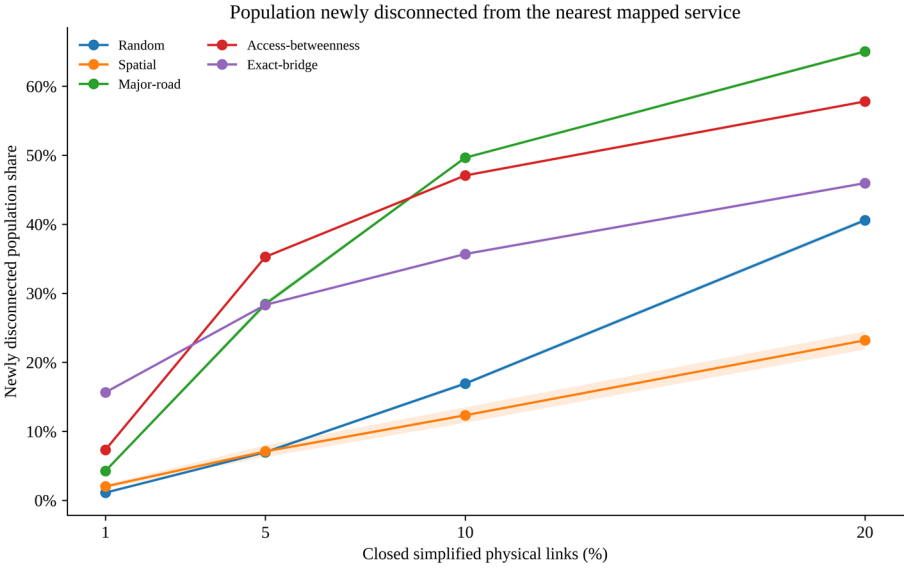

Fig. 3 Population newly disconnected from the nearest mapped service by closure mechanism. Baseline-unreachable population is excluded from new disconnection

removal remains lower at 16.93% and 40.59%, and spatial closure is lowest in the national averages at 12.33% and 23.19%.

Connected-only rerouting does not rise monotonically at high closure intensities. Under major-road targeting, it increases from 5.91 min at 1% to 13.85 min at 5%, is 13.46 min at 10%, and falls to 9.20 min at 20%. This decline is not an improvement in network performance. As more people become disconnected, they leave the connected-only distribution. Reporting rerouting and disconnection separately makes this selective attrition visible. A single penalized delay measure would conceal it.

Differences Among Service Types

Baseline distance alone does not determine service vulnerability. At moderate and high closure intensities, markets generally have the highest new-disconnection share, health the lowest, and fuel lies between them in most scenarios. At 10% random closure, the shares are 21.89% for markets, 19.39% for fuel, and 9.49% for health. Under 10% major-road targeting, they are 59.43%, 56.45%, and 33.06%. Under access-betweenness targeting, they are 56.22%, 51.47%, and 33.52%.

Bootstrap ranks show how these differences change with intensity. For market and fuel access, exact bridges have a 1.00 probability of producing the highest disconnection at 1% closure. At 5%, access-betweenness has a probability of 1.00 for markets and 0.989 for fuel, while exact bridges remain highest for health. At 10% and 20%, major-road targeting has a 1.00 probability of producing the highest market and fuel disconnection. For health, access-betweenness has probabilities of 0.863 and 0.991 at those intensities. These estimates show that no mechanism or service has a generally "highest expected rank".

Part of this ranking reflects the structure and completeness of the OSM service inventory. Markets and fuel stations are concentrated more strongly along commercial corridors, whereas the health layer is larger and combines a broader range of feature types. The comparison therefore concerns access to mapped OSM opportunities. It does not compare the operating capacity or quality of Yemen's food, fuel, and health systems.

Local Severity of Spatial Closures

National averages conceal much of the burden from spatially concentrated disruption (see Fig. 4; Table 4). At 1% spatial closure, the mean national new-disconnection share is 2.01%. Among people living within 25 km of the closure center, the mean is 59.64%. Within 50 km it is 31.00%, and within 100 km it is 11.78%. Within the realized closure footprint, 93.95% of the local population becomes newly disconnected. The average 1% footprint contains about 2.01% of the national population and has a radius of 21.0 km.

The gap between national and local exposure remains at higher intensities. At 5% closure, new disconnection is 7.10% nationally, 85.41% within 25 km, and 94.54% within the realized footprint. At 10%, the corresponding national mean is 12.33%, compared with 93.18% within 25 km and 94.97% within the footprint. At 20%, the national mean is 23.19%, while the local conditional values approach 95%. Spatial

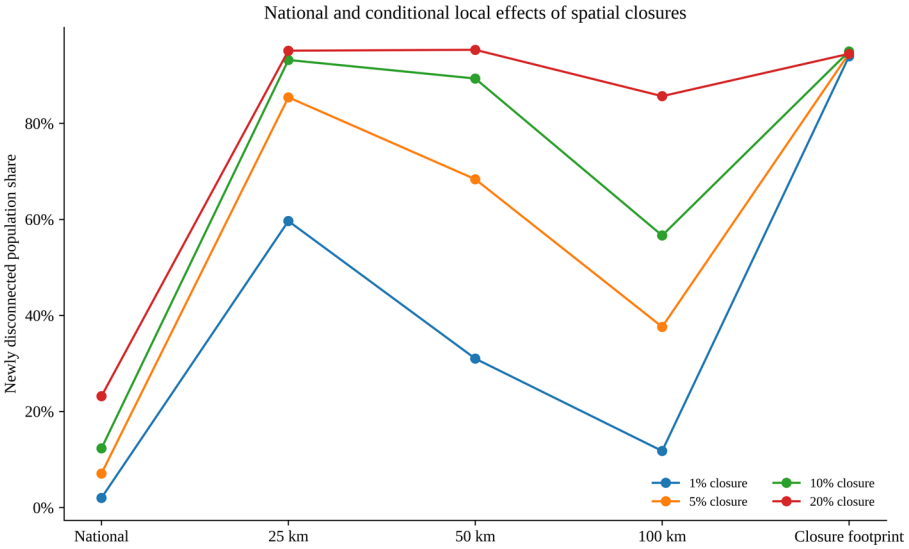

Fig. 4 National and conditional local new-disconnection shares under spatial closure. The figure shows why national averages cannot describe the burden borne by nearby populations

Table 4 Conditional local new-disconnection effects of spatial closures

Closure	National	Within 25 km	Within 50 km	Within 100 km	Within footprint	Population in footprint	Mean footprint radius (km)
1%	2.0%	59.6%	31.0%	11.8%	93.9%	2.0%	21.0
5%	7.1%	85.4%	68.4%	37.6%	94.5%	7.4%	53.9
10%	12.3%	93.2%	89.3%	56.6%	95.0%	12.9%	75.1
20%	23.2%	95.1%	95.3%	85.6%	94.5%	24.2%	132.1

Note. Values average 100 spatial replicates and the three service categories using the WorldPop demand layer

closure is thus least damaging only when effects are averaged nationally. For nearby populations, the losses are much more severe.

Robustness and Diagnostic Checks

The main estimates depend on choices about network topology, population weights, disconnection treatment, and strategic-link ranking. The following checks examine each choice and identify which interpretations remain stable.

Random-Removal Percolation and Topology

The percolation check tests whether limited random removal produces an implausible immediate collapse (see Fig. 5). New disconnection averaged across services is approximately 1.32% at 1% random removal, 2.37% at 2%, 6.73% at 5%, 16.91% at

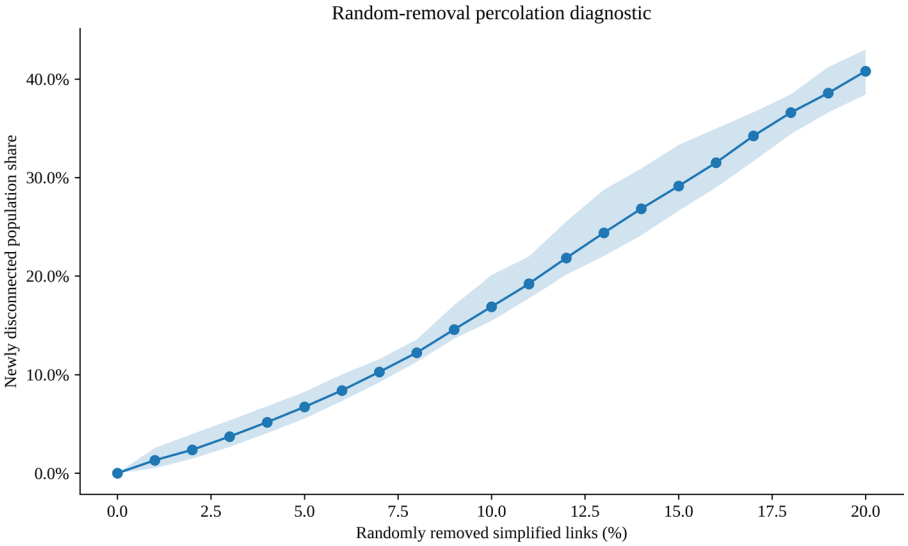

Fig. 5 Random-removal percolation diagnostic from 0% to 20% of simplified physical links. The line is the mean across services and ten replicates. The band is the replicate interval

10%, 29.14% at 15%, and 40.81% at 20%. The curve is shallow at low removal levels and steepens progressively. This is consistent with a large road graph that retains considerable redundancy under limited uniform random failure.

The corrected pattern follows from several implementation changes. Closures are applied to simplified physical links rather than intermediate geometry segments. The graph is undirected for this passability stress test. Demand and service nodes remain fixed. Baseline-unreachable pairs are excluded from new-disconnection counts, and the same service-node sets are used before and after closure. The diagnostics also show that the largest component contains 94.91% of nodes and 96.55% of WorldPop demand. These checks make the random scenario interpretable as a percolation experiment rather than a parsing or directionality artifact.

Population-Layer Robustness

Using the OSM settlement-weight layer instead of WorldPop lowers exposure estimates across much of the analysis (see Fig. 6). Across 60 mechanism-intensity-service cells, the mean new-disconnection share is 4.48% points lower with OSM weights, a mean relative difference of -16.98%. The mean absolute relative difference is 17.21%, and the 10-minute-or-disconnection share is lower by 4.77% points on average. Connected-only rerouting is also 15.19% lower on average. These differences affect both national exposure and the apparent vulnerability of rural and peri-urban populations.

The weak settlement-level correlations and the direction of these differences indicate that OSM tags underrepresent people outside a limited set of well-tagged settlements. The comparison explains why this demand layer is unsuitable as the primary specification.

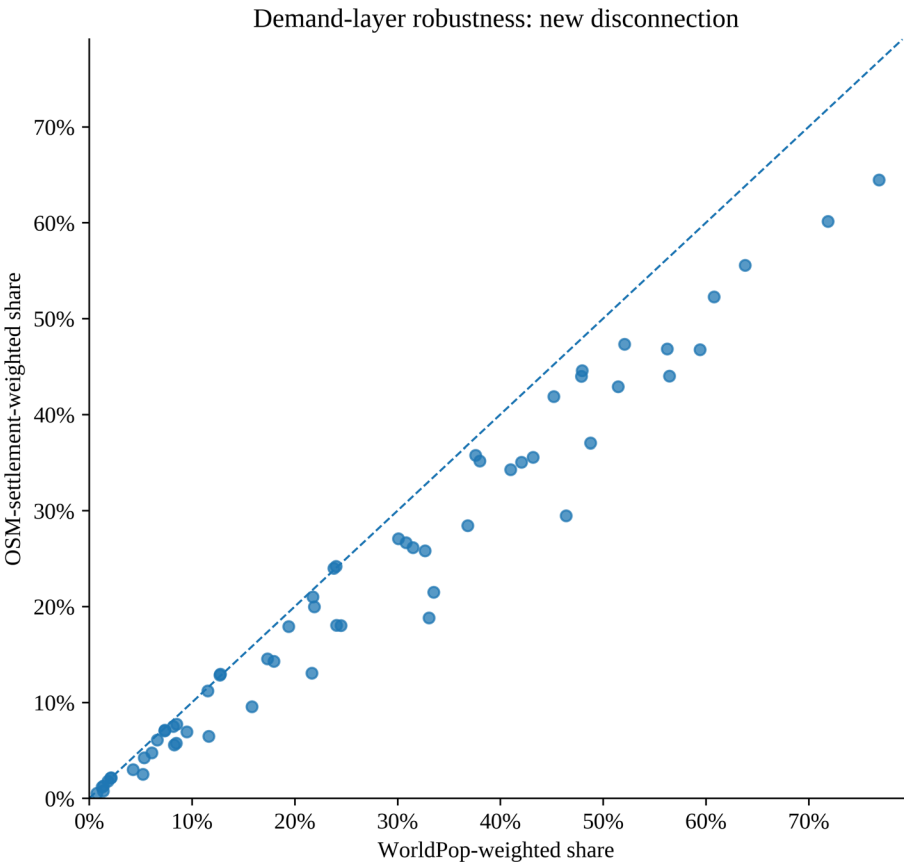

Fig. 6 WorldPop- versus OSM-settlement-weighted new-disconnection shares across all 60 scenario-service cells. The dashed diagonal denotes equality

Penalty Decomposition

The penalty decomposition illustrates why finite values assigned to loss of reachability should not be interpreted as observed travel delay. The sensitivity analysis considers assumed disconnection penalties of 60, 120, 240, and 480 minutes and separates, for each scenario, the population-mean connected-rerouting component from the population-mean component generated solely by the disconnection penalty (Fig. 7). The figure reports the 20% closure level, where the distinction is particularly clear.Connected rerouting is independent of the assumed disconnection penalty and therefore remains constant as the penalty changes. By contrast, the penalty component rises mechanically with the assumed number of minutes and with the population that becomes newly disconnected. The divergence is especially pronounced under major-road, access-betweenness, and exact-bridge targeting, where substantial population shares have lost network access by the 20% closure level. The random and spatial scenarios show the same mechanical relationship, although their absolute penalty contributions differ because their disconnection shares differ.This comparison shows

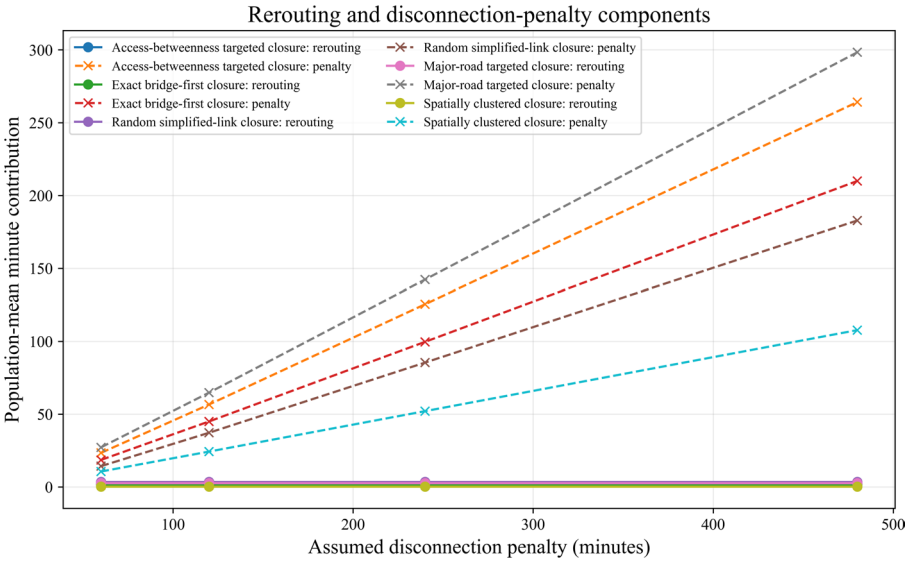

Fig. 7 Rerouting and disconnection-penalty components at 20% road-link closure under alternative finite disconnection penalties. Solid lines show the population-mean connected-rerouting contribution, which is unaffected by the assumed penalty. Dashed lines show the population-mean contribution generated by newly disconnected demand under assumed penalties of 60, 120, 240, and 480 minutes. Values are averaged across market, health, and fuel services and, for stochastic mechanisms, across scenario realizations

why adding a finite disconnection penalty to rerouting time can produce a combined measure whose magnitude is driven primarily by an analyst-selected constant rather than by observed detour time. A disconnected user does not literally experience a 60-, 120-, 240-, or 480-minute journey. These values are alternative conventions for representing loss of reachability. The main analysis therefore reports connected-only rerouting and newly disconnected population separately, while the penalty calculations are retained only as a sensitivity check. The substantive findings do not depend on selecting any one of the four penalty values.

Strategic-Ranking Validation and Sensitivity

Table 5 reports the ranked-edge validation and the aggregate access outcomes generated by three strategic weighting rules. The study does not treat the strategic analysis as a definitive ranking of bottlenecks. The baseline 80/20 access-betweenness/bridge score is compared with raw access betweenness and exact bridges, and outcomes are recalculated under 60/40 and 100/0 weights. The 60/40 ranking has a Spearman correlation of 0.989 with the baseline, but the top-tail overlap at 1% and 5% is low. A modest change in bridge weight can therefore reorder many links near the low-intensity cutoff.

Table 5 Strategic ranked-edge validation and aggregate outcome sensitivity

Panel A. Agreement among strategic edge-ranking definitions					
Comparison	1%	5%	10%	20%	Overall rank agreement
Baseline 80/20 vs. raw access betweenness	87.8%	73.1%	29.2%	16.3%	Score correlation: Spearman rho = 0.472; $p < 0.001$
Exact bridges within baseline 80/20 top set	6.5%	17.1%	58.6%	79.3%	Bridge concentration rises with the cutoff
60/40 vs. baseline 80/20: top-set Jaccard	3.4%	9.4%	41.4%	70.6%	Spearman rho = 0.989
100/0 pure-betweenness ordering vs baseline 80/20 ordering	87.8%	73.1%	29.2%	16.3%	Ordinal-ranking correlation:Spearman rho = 0.658
Panel B. Aggregate accessibility outcomes under alternative strategic weights					
Ranking definition	Closure	Connected-only added min	Newly disconnected	Loss >= 10 min or disconnected	Rerouting person-hours/trip (m)
60/40 betweenness/bridge	1%	0.04	8.27%	8.35%	0.022
60/40 betweenness/bridge	5%	0.83	22.36%	23.82%	0.425
60/40 betweenness/bridge	10%	0.89	35.93%	37.21%	0.378
60/40 betweenness/bridge	20%	3.33	46.02%	50.18%	1.173
80/20 baseline	1%	2.11	7.32%	11.77%	1.305
80/20 baseline	5%	6.94	35.28%	43.07%	2.756
80/20 baseline	10%	6.54	47.07%	53.39%	2.077
80/20 baseline	20%	6.21	57.80%	62.92%	1.619
100/0 pure access betweenness	1%	2.21	4.15%	9.29%	1.417
100/0 pure access betweenness	5%	7.11	33.89%	41.92%	2.879
100/0 pure access betweenness	10%	7.99	40.34%	48.44%	2.851
100/0 pure access betweenness	20%	9.57	55.28%	61.82%	2.345

Note. Panel A reports edge-set agreement at each closure cutoff. The two Spearman coefficients involving access betweenness measure different quantities. The coefficient of 0.472 is calculated directly between the continuous baseline 80/20 composite score and raw sampled access-betweenness values. The coefficient of 0.658 compares the complete ordinal edge positions produced by the 100/0 pure-betweenness ranking and the baseline 80/20 ranking after deterministic sorting and tie-breaking. The identical top-set Jaccard values in the two access-betweenness comparisons are therefore compatible with different overall score and ordinal-rank correlations. Panel B reports means across market, health, and fuel services. Connected-only rerouting is calculated for the population that remains connected after closure. Newly disconnected population excludes demand that was unreachable at baseline. The 80/20 definition is the main specification

Outcome sensitivity is greatest at 1% closure. Across services, mean new disconnection ranges from 4.15% under pure access betweenness to 8.27% under the 60/40 composite, compared with 7.32% under the 80/20 baseline. At 5%, the range

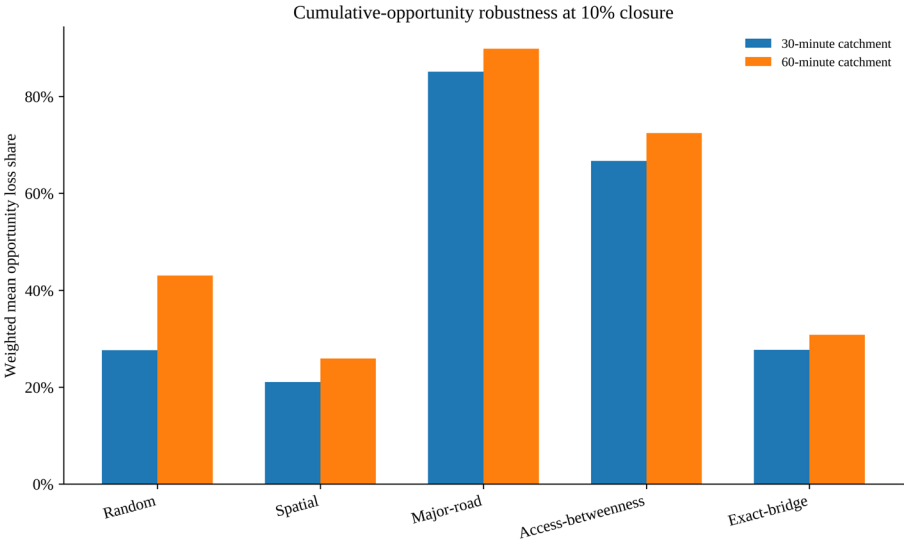

Fig. 8 Population-weighted cumulative-opportunity loss under the fixed 10% closure scenarios used for the robustness check. Values average market, health, and fuel opportunity loss for the 150-point demand sample

is 22.36% to 35.28%, at 10%, 35.93% to 47.07%, and at 20%, 46.02% to 57.80%. Rerouting can move in the opposite direction because bridge-heavy rankings disconnect localized groups while leaving little detour among survivors. The study therefore interprets strategic targeting as a family of plausible priority rules rather than a unique list of the "most important" links.

Cumulative-Opportunity Accessibility

The cumulative-opportunity analysis measures how many mapped services remain reachable within 30–60 min, rather than considering only the nearest one. At 10% random closure, the weighted mean loss across services is 27.6% within 30 min and 43.0% within 60 min (see Fig. 8). Spatial closure produces losses of 21.1% and 26.0%. The corresponding values are 85.1% and 89.8% under major-road targeting, 66.7% and 72.4% under access-betweenness targeting, and 27.7% and 30.8% under exact-bridge targeting.

The cumulative measure leads to the same broad interpretation as the nearest-service results, while showing an additional loss of choice. Major-road and access-betweenness targeting reduce the number of reachable opportunities even for some people who retain access to a nearest facility. This check remains constrained by OSM service completeness and the 150-point computational sample, but the main pattern does not depend solely on nearest-facility travel time.

Discussion

The evidence shifts attention away from a single headline estimate and toward the conditions under which different parts of the network become vulnerable. This section interprets those patterns, relates them to Yemen's service geography, and considers their implications for humanitarian and reconstruction planning.

Interpreting the Pattern of Network Vulnerability

The results describe several distinct forms of road-network vulnerability. Limited uniform random failure has comparatively small effects. Exact bridges disconnect particular populations early, major-road targeting produces long detours and increasingly widespread disconnection, and access-betweenness targeting removes links used frequently on population-to-service routes. Which mechanism appears most severe depends on the outcome being examined, whether disconnection, connected-only rerouting, loss of service choice, local exposure, or national exposure, and on the closure intensity.

A single link ranking or average delay cannot summarize these patterns. Bridges and other cut links may be essential to isolated communities even when they carry relatively few national shortest paths. Major corridors can force long detours over a wider area before users lose reachability altogether. Spatial blockades can impose extreme losses nearby while appearing modest in a national average. The Yemen results therefore reproduce the distinction between link importance and place exposure developed by Jenelius et al. (2006).

Markets, Fuel, Health, and the Import-Dependence Mechanism

Markets and fuel are generally more vulnerable than the mapped health layer at moderate and high closure intensities. The pattern is consistent with the stronger concentration of markets and fuel services along commercial corridors, Yemen's import-dependent economy, and its reliance on road corridors to distribute imported food, fuel, and other essentials (ACAPS, 2019; Coombs & Salah, 2023). A corridor disruption can lengthen household journeys to retail or distribution points and make it harder to move goods from ports or regional hubs to local markets. These transport frictions may contribute to scarcity, higher distribution costs, and pressure on household purchasing power, although the model does not estimate these economic effects (Coombs & Salah, 2023; OCHA, 2025).

However, these price and income effects are outside the model. It does not observe commodity flows, freight rates, retail prices, household budgets, or causal conflict exposure. The accessibility results identify a plausible spatial channel through which road disruption may interact with supply-chain costs and affordability. They neither quantify price pass-through nor attribute a purchasing-power loss to any simulated closure. This interpretation is limited to the spatial mechanism supported by the model.

Humanitarian and Reconstruction Implications

Humanitarian screening should combine national corridor analysis with measures of local conditional exposure. A national dashboard can make a spatial blockade appear minor even when most residents inside its footprint lose access. Conversely, bridge and major-road scenarios show how a small set of links can affect populations distributed across a wide area. At minimum, screening should consider exact cut links and bridge redundancy, population-to-service path centrality, and the population served locally by each corridor or cluster.

The service-specific findings also favor coordination across sectors. Fuel availability affects household mobility, market distribution, health-service operation, water pumping, and electricity generation. Market access concerns both household travel and the supply chains that keep destinations stocked. Health access depends on facility operation, staff, medicines, and referral capacity as well as road travel. The network model can identify where physical access is structurally fragile, but sector agencies need operational and needs data before prioritizing particular investments.

Limitations

This study is a stylized topological stress test rather than an analysis of observed closures. It does not use event locations, checkpoint records, frontlines, remote-sensing damage detection, or road-condition reports to identify links that were actually unavailable. The same mechanisms could represent disruption from floods, landslides, earthquakes, maintenance, or administrative restrictions. Yemen supplies the road geometry, population distribution, service mapping, and policy context, but the scenario estimates are not causal effects of conflict.

OpenStreetMap quality varies across space and feature types. Roads may be absent, geometrically inaccurate, misclassified, or impassable despite being mapped. Only 1.6% of physical links have observed maxspeed information, so most travel times rely on road-class defaults. The undirected graph omits one-way and turn restrictions, as well as congestion, surface condition, seasonal passability, security delay, checkpoint waiting, and travel-mode differences. These omissions do not all bias results in the same direction. Excluding congestion and checkpoint delay may understate travel time, whereas excluding informal routes, mode substitution, trip rescheduling, destination substitution, and household adaptation may overstate the effect of a formal-road closure.

The service layer identifies mapped features rather than verified functioning services. A health feature may be inactive or offer only limited care, a market tag does not report stock or affordability, and a mapped fuel station may have no fuel. The study does not model capacity, quality, opening hours, referral relationships, or competition among facilities. The cumulative-opportunity check relaxes the nearest-facil-

ity assumption to some extent, but it still treats mapped opportunities equally and is based on a 150-point sample.

WorldPop is a modeled population surface, not census microdata, and aggregation to 5-km cells smooths variation within each cell. Snapping cells to the road graph adds another approximation. The mean distance is 1.01 km and the 95th percentile is 3.11 km. The population data are not disaggregated by sex or gender. Women and girls in Yemen may face gender-specific transport costs, social restrictions on movement, unequal access to private vehicles, caregiving-related travel demands, and barriers to maternal and reproductive health services (Aljounaidi, 2010). In parts of the country, mahram requirements have also required women to be accompanied by a male family member when travelling (United Nations Population Fund [UNFPA], 2023). Because aggregate gridded data cannot represent these constraints, the model may conceal important gender differences in effective accessibility. Consistent with the SAGER guidelines, the study states this limitation rather than assuming behaviorally homogeneous access (Heidari et al., 2016).

The analysis reports person-hours per trip but does not observe how often people make each type of trip. It therefore avoids monthly or annual aggregation and monetary valuation. This removes a simple headline cost, but it also prevents uncertain behavioral and income assumptions from determining the conclusions. Future research could combine verified closure histories with survey or mobile-phone mobility data, verified service status, freight flows, price series, and demographic disaggregation to estimate realized impacts.

Conclusion

The study assesses Yemen's road-access vulnerability with a gridded population surface, simplified physical links, transparent strategic rankings, and separate measures of rerouting and disconnection. Limited random removal does not collapse national access. Vulnerability instead depends on which links are removed and on the spatial scale of measurement. Exact bridges produce the largest early disconnection, access-betweenness targeting is especially disruptive at moderate closure, and major-road targeting produces the greatest high-intensity disconnection together with substantial detours. Spatial closures create severe local losses that national averages largely conceal.

The contribution is methodological and diagnostic. Open road, service, and gridded population data can be combined to distinguish detour, disconnection, local and national exposure, and loss of service choice. The analysis also shows why demand-layer validation, percolation checks, strategic-ranking sensitivity, and penalty decomposition affect substantive interpretation rather than merely technical presentation. The results may inform humanitarian and reconstruction screening, but decisions about particular corridors or facilities require verified road conditions, operational service data, and local knowledge.

Appendix 1. Exact OpenStreetMap Service Tag Queries

Table 6 Reproducible service-feature queries

Service	OSM key	OSM value	Logic
Market	amenity	marketplace	OR within and across listed keys
Market	shop	supermarket	OR within and across listed keys
Market	shop	convenience	OR within and across listed keys
Market	shop	general	OR within and across listed keys
Market	shop	greengrocer	OR within and across listed keys
Health	amenity	hospital	OR within and across listed keys
Health	amenity	clinic	OR within and across listed keys
Health	amenity	doctors	OR within and across listed keys
Health	healthcare	hospital	OR within and across listed keys
Health	healthcare	clinic	OR within and across listed keys
Health	healthcare	doctor	OR within and across listed keys
Health	healthcare	centre	OR within and across listed keys
Health	healthcare	center	OR within and across listed keys
Fuel	amenity	fuel	OR within and across listed keys

Appendix 2. Operational Definitions

Table 7 Operational definitions

Term	Definition
Simplified physical link	An undirected road connection between intersections or terminal endpoints after removal of intermediate geometry nodes.
Baseline reachable	A demand-service pair for which at least one mapped service is reachable on the intact graph.
Connected-only rerouting	Scenario minus baseline travel time among people who remain connected after closure.
Newly disconnected	Population reachable at baseline but unable to reach any mapped service of that type after closure.
Access loss>=x minutes or disconnected	Population with connected rerouting of at least x minutes plus population newly disconnected.
Rerouting person-hours per trip	Sum of population-weighted connected rerouting minutes divided by 60.
Spatial footprint	The circular area extending from the sampled closure center to the most distant removed link midpoint.
Access betweenness	Sampled frequency with which a physical link lies on shortest paths from population demand nodes to service nodes.
Exact bridge	A graph edge whose removal increases the number of connected components.

Appendix 3. Full Service-Specific Results With Uncertainty

Table 8 Full results for all mechanisms, closure levels, and service types

Mechanism	Closure	Service	Connected-only minutes, mean (95% CI)	Newly disconnected, mean (95% CI)	Loss>=10 min/disconnected, mean (95% CI)	Person-hours/trip (m)	*n*
Random	1%	Markets	1.58 (1.48–1.68)	1.2% (1.2–1.3)	4.8% (4.6-5.0)	1.051	100
Random	1%	Health	0.15 (0.14–0.16)	0.7% (0.7–0.8)	1.0% (1.0-1.1)	0.101	100
Random	1%	Fuel	0.89 (0.84–0.95)	1.4% (1.3–1.5)	3.8% (3.7-4.0)	0.596	100
Random	5%	Markets	8.25 (7.95–8.58)	8.5% (8.3–8.7)	22.8% (22.5–23.2)	5.084	100
Random	5%	Health	0.78 (0.76–0.81)	4.3% (4.1–4.4)	6.0% (5.8–6.2)	0.511	100
Random	5%	Fuel	4.70 (4.56–4.85)	8.2% (8.0-8.4)	18.4% (18.1–18.7)	2.915	100
Random	10%	Markets	13.00 (12.56–13.44)	21.9% (21.5–22.2)	39.6% (39.3–40.0)	6.823	100
Random	10%	Health	1.58 (1.55–1.61)	9.5% (9.3–9.7)	13.1% (12.9–13.4)	0.973	100
Random	10%	Fuel	8.38 (8.07–8.71)	19.4% (19.0-19.7)	32.4% (32.1–32.6)	4.552	100
Random	20%	Markets	10.92 (10.42–11.45)	52.1% (51.7–52.5)	61.6% (61.3–61.9)	3.475	100
Random	20%	Health	2.80 (2.76–2.84)	24.5% (24.2–24.8)	30.6% (30.3–30.8)	1.440	100
Random	20%	Fuel	6.04 (5.79–6.30)	45.2% (44.9–45.5)	52.6% (52.3–52.8)	2.216	100
Spatially clustered	1%	Markets	0.13 (0.09–0.19)	2.1% (1.8–2.4)	2.4% (2.1–2.7)	0.088	100
Spatially clustered	1%	Health	0.01 (0.01–0.01)	1.8% (1.6-2.0)	1.8% (1.6–2.1)	0.004	100
Spatially clustered	1%	Fuel	0.10 (0.05–0.15)	2.1% (1.8–2.4)	2.3% (2.0-2.7)	0.063	100
Spatially clustered	5%	Markets	0.29 (0.21–0.38)	7.4% (6.5–8.2)	7.9% (7.0-8.8)	0.181	100
Spatially clustered	5%	Health	0.02 (0.02–0.02)	6.6% (5.9–7.4)	6.7% (5.9–7.4)	0.012	100
Spatially clustered	5%	Fuel	0.24 (0.15–0.36)	7.3% (6.5–8.3)	7.8% (6.9–8.6)	0.151	100
Spatially clustered	10%	Markets	0.32 (0.24–0.42)	12.8% (11.7–13.9)	13.3% (12.0-14.5)	0.183	100
Spatially clustered	10%	Health	0.02 (0.02–0.03)	11.5% (10.5–12.6)	11.6% (10.7–12.5)	0.013	100
Spatially clustered	10%	Fuel	0.20 (0.12–0.31)	12.7% (11.6–13.9)	13.1% (11.8–14.2)	0.117	100
Spatially clustered	20%	Markets	0.61 (0.42–0.84)	24.0% (22.6–25.3)	24.9% (23.5–26.2)	0.312	100
Spatially clustered	20%	Health	0.02 (0.02–0.03)	21.8% (20.5–23.0)	21.8% (20.7–23.1)	0.013	100
Spatially clustered	20%	Fuel	0.35 (0.24–0.49)	23.8% (22.4–25.1)	24.3% (23.0-25.6)	0.179	100
Major-road targeted	1%	Markets	11.21 (10.76–11.68)	6.1% (5.8–6.4)	24.8% (24.5–25.2)	7.108	100

Table 8 (continued)

Mechanism	Closure	Service	Connected-only minutes, mean (95% CI)	Newly disconnected, mean (95% CI)	Loss>=10 min/disconnected, mean (95% CI)	Person-hours/trip (m)	*n*
Major-road targeted	1%	Health	0.74 (0.72–0.77)	1.4% (1.3–1.4)	2.9% (2.8-3.0)	0.501	100
Major-road targeted	1%	Fuel	5.78 (5.61–5.96)	5.3% (5.1–5.6)	17.9% (17.6–18.2)	3.698	100
Major-road targeted	5%	Markets	23.72 (23.18–24.27)	36.8% (36.4–37.3)	57.4% (57.0-57.8)	10.011	100
Major-road targeted	5%	Health	2.43 (2.39–2.46)	15.8% (15.4–16.2)	21.7% (21.3–22.1)	1.392	100
Major-road targeted	5%	Fuel	15.40 (14.87–15.97)	32.7% (32.2–33.2)	48.8% (48.5–49.2)	6.976	100
Major-road targeted	10%	Markets	22.89 (22.24–23.49)	59.4% (59.2–59.6)	72.5% (72.4–72.6)	6.119	100
Major-road targeted	10%	Health	3.25 (3.23–3.28)	33.1% (33.0-33.2)	40.1% (40.0-40.2)	1.480	100
Major-road targeted	10%	Fuel	14.23 (14.01–14.46)	56.5% (56.3–56.6)	68.4% (68.3–68.5)	4.105	100
Major-road targeted	20%	Markets	12.30 (11.73–12.84)	76.8% (76.6–77.1)	81.9% (81.7–82.1)	1.816	100
Major-road targeted	20%	Health	3.82 (3.75–3.89)	46.4% (46.1–46.6)	52.7% (52.5–52.9)	1.389	100
Major-road targeted	20%	Fuel	11.48 (11.12–11.83)	71.9% (71.6–72.1)	78.0% (77.8–78.2)	2.099	100
Access-betweenness	1%	Markets	4.40	8.5%	17.2%	2.710	1
Access-betweenness	1%	Health	0.43	5.2%	6.2%	0.280	1
Access-betweenness	1%	Fuel	1.49	8.3%	12.0%	0.923	1
Access-betweenness	5%	Markets	11.98	43.2%	54.1%	4.530	1
Access-betweenness	5%	Health	1.76	21.7%	25.5%	0.941	1
Access-betweenness	5%	Fuel	7.09	41.0%	49.6%	2.798	1
Access-betweenness	10%	Markets	10.61	56.2%	64.7%	3.065	1
Access-betweenness	10%	Health	2.02	33.5%	37.3%	0.912	1
Access-betweenness	10%	Fuel	6.99	51.5%	58.1%	2.255	1
Access-betweenness	20%	Markets	9.77	63.8%	70.4%	2.311	1
Access-betweenness	20%	Health	2.88	48.8%	52.8%	1.000	1
Access-betweenness	20%	Fuel	5.98	60.8%	65.6%	1.547	1
Exact-bridge	1%	Markets	0.96	17.3%	19.2%	0.531	1

Table 8 (continued)

Mechanism	Closure	Service	Connected-only minutes, mean (95% CI)	Newly disconnected, mean (95% CI)	Loss >= 10 min/disconnected, mean (95% CI)	Person-hours/trip (m)	*n*
Exact-bridge	1%	Health	0.09	11.6%	11.8%	0.055	1
Exact-bridge	1%	Fuel	0.03	18.0%	18.0%	0.018	1
Exact-bridge	5%	Markets	1.28	30.1%	32.6%	0.601	1
Exact-bridge	5%	Health	0.30	24.1%	24.7%	0.156	1
Exact-bridge	5%	Fuel	0.09	30.8%	31.0%	0.041	1
Exact-bridge	10%	Markets	1.37	37.6%	39.9%	0.570	1
Exact-bridge	10%	Health	0.51	31.5%	32.5%	0.239	1
Exact-bridge	10%	Fuel	0.61	38.0%	38.2%	0.252	1
Exact-bridge	20%	Markets	6.27	47.9%	54.4%	2.166	1
Exact-bridge	20%	Health	1.40	42.1%	44.3%	0.550	1
Exact-bridge	20%	Fuel	2.31	47.9%	51.8%	0.803	1

Note. Intervals are percentile bootstrap intervals across 100 stochastic replicates. Deterministic access-betweenness and exact-bridge scenarios are point estimates and have $n = 1$

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Data Availability Road and service data were derived from the OpenStreetMap Yemen extract yemen-260725.osm.pbf, created by OpenStreetMap contributors and distributed by Geofabrik GmbH under the Open Database Licence. The PBF header records a data timestamp of 25 July 2026 at 20:21:51 UTC. Population demand was derived from the 2025 constrained WorldPop R2025A v1 population-count raster at approximately 100-m resolution (DOI: 10.5258/SOTON/WP00839), licensed under CC BY 4.0.

Declarations

Ethics Approval Not applicable. The study uses aggregate, publicly available geospatial data and does not involve human participants or individual-level records.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

Dual-use Statement The analysis evaluates road-link importance for access to essential civilian services in an active conflict setting. Table 5 reports the ranking-validation statistics and aggregate access outcomes needed to assess the strategic specifications. It does not identify individual links or publish their coordinates. The method and source data are public and the intended use is humanitarian and infrastructure planning.

Use of Generative Artificial Intelligence Generative AI was used to assist with code review and language editing. All analyses were executed by the author, and the author checked and approved all calculations, interpretations, references, and final text.

Data and Code Availability The code used for data processing, network construction, accessibility analysis, road-closure simulations, robustness checks, and figure production is available at https://doi.org/10.5281/zenodo.22721057. The analysis was run with master random seed 260725, using 100 replicates for each stochastic closure mechanism, 10 replicates for the independent percolation diagnostic, 60 population-demand sources and 60 service targets for sampled access betweenness, 150 population-weighted demand nodes for the cumulative-opportunity check, and 2,000 bootstrap draws. The analysis uses a Yemen OpenStreetMap PBF extract dated 25 July 2026 for the road network and mapped market, health, and fuel features, and the WorldPop 2025 R2025A v1 constrained population-count surface for population demand. OpenStreetMap and WorldPop remain available from their respective data providers under their applicable licences and are not redistributed through the code repository. The repository records the software environment and analysis configuration required to reproduce the workflow.

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References

ACAPS. (2019, April 12). Yemen: Drivers of food insecurity. https://www.acaps.org/en/countries/archives/detail/yemen-drivers-of-food-insecurity

Aljounaidi, L. (2010). *Gender and transport in MENA: Case studies from West Bank Gaza and Yemen (MENA Knowledge and Learning Quick Notes Series No. 21)*. World Bank. https://hdl.handle.net/10986/10935

Barrington-Leigh, C., & Millard-Ball, A. (2017). The world's user-generated road map is more than 80% complete. *PLOS ONE*, *12*(8), e0180698. https://doi.org/10.1371/journal.pone.0180698

Berdica, K. (2002). An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy*, *9*(2), 117–127. https://doi.org/10.1016/S0967-070X(02)00011-2

Bondarenko, M., Priyatikanto, R., Tejedor-Garavito, N., Zhang, W., McKeen, T., Cunningham, A., Woods, T., Hilton, J., Cihan, D., Nosatiuk, B., Brinkhoff, T., Tatem, A., & Sorichetta, A. (2025). Constrained estimates of 2015–2030 total number of people per grid square at a resolution of 3 arc (approximately 100 m at the equator), R2025A version v1 [Data set]. *WorldPop School of Geography and Environmental Science University of Southampton*. https://doi.org/10.5258/SOTON/WP00839

Callaway, D. S., Newman, M. E. J., Strogatz, S. H., & Watts, D. J. (2000). Network robustness and fragility: Percolation on random graphs. *Physical Review Letters*, *85*(25), 5468–5471. https://doi.org/10.1103/PhysRevLett.85.5468

Coombs, C., & Salah, S. A. (2023, January 16). *The war on Yemen's roads.* Sana'a Center for Strategic Studies. https://sanaacenter.org/publications/policy-research/19304

Duan, Y., & Lu, F. (2014). Robustness of city road networks at different granularities. *Physica A: Statistical Mechanics and its Applications*, *411*, 21–34. https://doi.org/10.1016/j.physa.2014.05.073

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, *12*(2), 127–140. https://doi.org/10.1016/j.jtrangeo.2003.10.005

Haklay, M. (2010). How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and Planning B: Planning and Design*, *37*(4), 682–703. https://doi.org/10.1068/b35097

Hansen, W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners*, *25*(2), 73–76. https://doi.org/10.1080/01944365908978307

Heidari, S., Babor, T. F., De Castro, P., Tort, S., & Curno, M. (2016). Sex and gender equity in research: Rationale for the SAGER guidelines and recommended use. *Research Integrity and Peer Review*, *1*., Article 2. https://doi.org/10.1186/s41073-016-0007-6

Inter-Agency Standing Committee. (2023). *Operational guidance: Data responsibility in humanitarian action* (2nd ed.). https://interagencystandingcommittee.org/system/files/2023-04/IASC%20Operational%20Guidance%20on%20Data%20Responsibility%20in%20Humanitarian%20Action%2C%202023.pdf

Jenelius, E., Petersen, T., & Mattsson, L. G. (2006). Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, *40*(7), 537–560. https://doi.org/10.1016/j.tra.2005.11.003

Mattsson, L. G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems – A discussion of recent research. *Transportation Research Part A: Policy and Practice*, *81*, 16–34. https://doi.org/10.1016/j.tra.2015.06.002

OpenStreetMap contributors. (2026, July 25). *Yemen OpenStreetMap data extract (yemen-260725.osm.pbf)* [Data set]. Geofabrik GmbH. https://download.geofabrik.de/asia/yemen.html

Schouten, P., van den Boogaard, V., Gallien, M., Thakur, S., & Weigand, F. (2024). *The politics of passage: Roadblocks, taxation and control in conflict* (DIIS Working Paper, Vol. 2024; Roadblocks and Revenues, No. 01). Danish Institute for International Studies. https://research.diis.dk/en/publications/the-politics-of-passage-roadblocks-taxation-and-control-in-confli/

Schouten, P., van den Boogaard, V., Gallien, M., Thakur, S., & Weigand, F. (2026). The politics of passage: Studying checkpoints and claim making in conflict-affected settings. *Development and Change*, *57*(3), 421–440. https://doi.org/10.1111/dech.70067

Stevens, F. R., Gaughan, A. E., Linard, C., & Tatem, A. J. (2015). Disaggregating census data for population mapping using random forests with remotely-sensed and ancillary data. *PLOS ONE*, *10*(2), e0107042. https://doi.org/10.1371/journal.pone.0107042

Tatem, A. J. (2017). WorldPop, open data for spatial demography. *Scientific Data*, *4*, 170004. https://doi.org/10.1038/sdata.2017.4

Taylor, M. A. P., Sekhar, S. V. C., & D'Este, G. M. (2006). Application of accessibility based methods for vulnerability analysis of strategic road networks. *Networks and Spatial Economics*, *6*(3–4), 267–291. https://doi.org/10.1007/s11067-006-9284-9

United Nations Office for the Coordination of Humanitarian Affairs. (2025, January 15). *Yemen humanitarian needs and response plan 2025 (January 2025)*.https://yemen.un.org/en/287505-yemen-humanitarian-needs-and-response-plan-2025-january-2025

United Nations Population Fund. (2023, February 7). UNFPA humanitarian response in Yemen 2023. https://yemen.unfpa.org/en/publications/unfpa-humanitarian-response-yemen-2023

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