Sensing Urban Vulnerability During a Heatwave: Mobile-Network Trajectories and Well-Being Indicators for Heat-Emergency Preparedness in Bologna

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***Abstract*—Heatwaves are among the deadliest weather-related hazards in Europe, yet little is known about how they reshape the flow of people toward emergency care at the scale of a single city. We reconstruct individual-level trajectories of mobile devices reaching Sant'Orsola-Malpighi Hospital in Bologna on the peak day of the July 2025 heatwave from about 42 GB of passive mobile network measurements (TIM (MDT dataset)), and compare them with a matched control day one month earlier. Trajectories (409 on the heatwave day vs. 173 on the control day) are aggregated over the 19 postal codes of the city and enriched with urban green coverage, buildings, residential prices and age structure. Six network-theoretic and spatial analyses show that the heatwave concentrates hospital-bound mobility on a few transit corridors, raises the number of inter-zone transitions per trajectory, and weakens habitual mobility communities, while heat-related emergency department visits and a composite vulnerability index are strongly spatially clustered with a hotspot in the south-eastern periphery. The results identify concrete spatial targets for heat-emergency preparedness and illustrate what passive network data can add to urban climate adaptation.**

***Index Terms*—heatwave, urban mobility, mobile network data, trajectory reconstruction, emergency department, spatial analysis, community detection**

I. Introduction and Motivation

Extreme heat is the leading weather-related cause of death in Europe: the 2003 heatwave caused more than 70,000 excess deaths [1]. Its burden is not distributed uniformly within cities: exposure interacts with the built environment, as neighbourhoods with little vegetation and dense construction develop stronger microclimatic stress, motivating spatial vulnerability indices intended to guide local public-health action.

What such vulnerability maps do not capture is *movement*. When a heatwave peaks, part of the population travels—to emergency departments, to cooler places, to relatives—and the spatial pattern of this response determines where the burden actually lands. Mobile phone data are the standard instrument for observing such behaviour at scale and have proven informative in large-scale emergencies, but heatwaves differ from sudden shocks: they unfold over days, leave infrastructure intact, and act selectively on health. To our knowledge, the reorganisation of *hospital-directed* mobility during a heat emergency has not been examined with individual-level network data.

This work addresses that gap for Bologna, Italy, on 9 July 2025, the local peak of a heatwave that affected much of southern Europe that summer. We reconstruct the trajectories of all mobile devices travelling to Sant'Orsola-Malpighi Hospital—the city's main hospital and emergency department (ED)—and repeat the reconstruction on a control day with ordinary June temperatures (9 June 2025), asking not only *where* hospital-bound trips originate under heat stress, but *how* they traverse the city, whether the underlying vulnerability is spatially clustered, and whether the emergency dissolves the habitual structure of urban mobility.

II. Data and Methods

A. Data

The primary dataset consists of passive probe measurements collected by the operator TIM over Bologna on 9 July 2025 (about 42 GB uncompressed), each record carrying an anonymised device identifier, a session identifier, a timestamp and network-derived coordinates; a matched extract from 9 June 2025 serves as the control day, with no content or subscriber identity present. These are joined with heat-related ED records for Sant'Orsola-Malpighi (ICD-9 diagnosis), the 19 postal-code (CAP) polygons, census age structure, OpenStreetMap green areas and building footprints via `osmnx` [2], and OMI-based prices.

B. Trajectory Reconstruction

The 42 GB stream is processed in parallel by chunks, grouping records by radio session into a session centroid with its time window. A device is counted as a hospital visitor if a segment falls within 400 m of the main entrance; to isolate genuinely *inbound* mobility—rather than residents or staff already on site—we require its earliest position to lie at least 800 m from the hospital and keep only multi-segment devices. This yields 409 inbound trajectories on the heatwave day and 173 on the control day, each converted into an ordered sequence of postal codes by a spatial join with the CAP polygons.

C. Linking Mobility to Health

The two data streams are joined at the postal code, the finest unit both carry in common, and linked in two complementary ways. First, the reconstructed trajectory origins give a *movement-based* estimate of where hospital demand comes from, which we cross-check against the *residence-based* postal code recorded in the ED accesses, so that mobility signal and clinical record corroborate one another. Second, for every zone we combine its clinical burden with its environmental deficit into a single composite vulnerability index $V_c = \widehat{E}_c - \widehat{G}_c$, where $\widehat{E}_c$ is the min–max normalised count of heat-related ED visits of residents of zone c and $\widehat{G}_c$ the normalised green-to-buildings ratio. A zone therefore scores high only when a high heat-health burden coincides with little green cooling capacity; each zone is further characterised by its residential price and its share of residents aged 65 and over.

D. Network Analyses

On this base layer we apply six analyses. *(net1)* A directed, flow-weighted CAP→CAP transit network, whose betweenness identifies the zones through which hospital-bound trips are routed, and *(net1b)* its demand-weighted analogue on the real Bologna drive graph (OSM; 5,470 nodes), localising the same corridors at street level. *(net2)* Road-network distances, giving a detour ratio and an access-adjusted vulnerability that adds the normalised road distance to care to V_c. *(net3)* Global and local Moran's I [3] (999 permutations), testing whether burden and vulnerability are spatially clustered. *(net4)* A path-complexity comparison of three per-trajectory statistics—the number of distinct zones visited, the number of inter-zone transitions, and the *visit entropy*, i.e. the Shannon entropy $H = -\sum_i p_i \log_2 p_i$ (in bits) of the zones visited by a device, where p_i is the frequency of zone i in the device's (repeat-collapsed) sequence of visited zones, so that H measures how evenly the visits are spread across zones—compared between the two days with a permutation Kolmogorov–Smirnov (KS) test. *(net5)* Louvain community detection [4] on a device co-presence network, whose modularity Q measures how compartmentalised mobility is; and *(net6)* a city-wide dwell analysis of stops inside OSM parks.

III. Results

A. Origins and Transit Corridors

The heatwave roughly doubled inbound volume without widening the catchment (median origin distance about 2.1 km on both days), drawing disproportionately from peripheral postal codes with low green ratios and higher elderly shares. The flow network concentrated on a small set of corridors (Table I): CAP 40126 dominated betweenness on the heatwave day (0.56 vs. 0.15), 40137 and 40134 became corridors *only* under heat, and the ordinary corridor 40129 lost its role entirely. At street level (net1b) about 70% of routes funnel through a handful of approach streets around the hospital gate: the emergency reroutes flows, it does not merely amplify them.

TABLE I

FLOW-WEIGHTED BETWEENNESS CENTRALITY OF SELECTED POSTAL CODES IN THE CAP→CAP TRANSIT NETWORK, HEATWAVE VS. CONTROL DAY.

CAP	Betw. (heatwave)	Betw. (control)	Δ
40126	0.564	0.152	$+0.412$
40137	0.102	0.000	$+0.102$
40129	0.000	0.304	-0.304

B. Accessibility and Spatial Clustering

Road distances to the hospital exceeded Euclidean ones by up to a factor of two, so the access-adjusted vulnerability index peaked in the periphery. Both heat-related ED visits (Moran's $I = 0.52$) and the composite vulnerability index ($I = 0.37$) were significantly spatially clustered ($p = 0.001$), while neither the green ratio nor the elderly share was on its own. Local Moran statistics placed a high–high hotspot at CAP 40138 ($p = 0.049$)—the hospital's own quadrant—and a low–low coldspot at 40123 in the green south-west ($p = 0.003$).

C. Path Complexity and Communities

Distinct-zone count and visit entropy were statistically indistinguishable between the two days, but inter-zone *transitions* increased (median 3 vs. 2; KS $D = 0.11$, $p = 0.04$), consistent with less direct paths under heat. Louvain modularity of the co-presence network dropped from $Q = 0.066$ to 0.035, indicating that hospital-directed flows cut across the habitual functional districts. Finally, a city-wide dwell analysis (net6) confirmed that residents use parks as a heat refuge—the share of daytime stops inside a park rose from 7.6% to 11.7% under heat—so the low-burden green south-west is exactly where the cooling capacity flagged by V_c is consumed.

IV. Discussion and Conclusion

These results translate into concrete guidance. The access-adjusted index separates two operationally distinct kinds of at-risk zone: those whose problem is *intrinsic* vulnerability—a high heat-health burden with little green, such as 40139, 40127 and 40138—which call for urban greening and outreach to elderly residents, and those whose problem is mainly *distance* from care—such as 40132 and 40128—which call for transport provision or decentralised services. The transit corridors show where capacity matters during an alert, and the tested LISA hotspot at 40138 gives a defensible priority area for cooling-centre placement. Limitations include the single-day comparison, network localisation error, and the fact that devices are not patients, mitigated by the agreement between trajectory origins and the ED residence records. Nonetheless, routinely collected operator data resolve the mobility dimension of heat vulnerability that static maps miss, at the resolution at which municipal heat plans are written.

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