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Mixture models uncover polycentric urban structure from mobility networks

Keywords: Spatial networks, mobility, urban networks, polycentricity

Extended Abstract

The modern city is often characterized by a tension between centralizing forces and decentralizing forces. Human mobility patterns offer a powerful lens to understand a city's dynamic structure, often revealing complexities hidden in static maps of population or land use. Tracking where and when people travel – their daily moves across the city – yields a map of functional urban connectivity, effectively the "revealed preference" of residents using and experiencing the city. Here we exploit GPS mobility data for urban residents in cities across Germany, France and the United Kingdom to develop a method for understanding how cities balance the forces of centralization and decentralization. In doing so, we find regularities in how people distribute activities in space with implications social mixing, productivity, and sustainability. We analyze GPS traces for 50 million residents across 226 functional urban areas in France, Germany, and the United Kingdom. We use home- and stop-detection to define each *trip* of length d_{ij}, the distance between home and stop. Each pooled home hexagon (H3 level 9) is assigned a vector of trip distances. Because these length distributions are comprised of trips generated from different processes, which include leisure activities and commutes, we employ finite *mixture models* to separate shorter-range routine mobility from longer-range travel within a single, interpretable framework.

Methods. For each home hexagon we model the empirical distribution of trip lengths with a three-component Gamma mixture

$$f(d) = \sum_{c \in \{p,m,d\}} \pi_c \Gamma(d \mid \alpha_c, \beta_c),$$

representing *proximal*, *medial*, and *distal* mobility scales. Mixture parameters $(\pi_c, \alpha_c, \beta_c)$ are obtained by maximum-likelihood expectation–maximization and the components are ordered by increasing mean $\hat{\mu}_c = \alpha_c/\beta_c$. The resulting means $(\hat{\mu}^p, \hat{\mu}^m, \hat{\mu}^d)$ represent the typical trip distance within each component, or scale, while the weights (π^p, π^m, π^d) quantify the share of all trips undertaken in that scale for the neighborhood in question. To understand how these values vary with respect to urban spatial structure, we estimate an urban center for each city by taking the centroid of the busiest location by GPS pings and computing each neighborhood's distance to that centroid.

We demonstrate our approach on London in Fig. **1a** and **b**, where we can see that as a neighborhood gets farther away from the center—which in London is near Piccadilly Circus—the distal mean $\hat{\mu}^d$ grows, suggesting that these communities need to travel farther to access important services or jobs. The proximal $\hat{\mu}^p$ distances do not systematically vary by distance to the center, suggesting that local activity operates at a similar scale no matter than neighborhood, and medial $\hat{\mu}^m$ distances scale but less so than $\hat{\mu}^d$. We document an interesting fact in London: because our modeling approach is agnostic to what kinds of trips it decomposes into constituent distributions, it detects a distal component in central locations, which represents trips away from the center. These trips constitute smaller proportions for their neighborhoods relative to suburban ones, but it suggests urban residents might gain flexibility and leisure time. Fitting mixture models to $\sim 20,000$ neighborhoods across ~ 200 cities in Europe, we see a number of important regularities, shown in Fig. **1c**. Across all cities, as in London, $\hat{\mu}^p$ is typically location invariant while $\hat{\mu}^m$ and $\hat{\mu}^d$ vary more. The insets in Fig. **1c** show the slope of the best fit line for each city, with brigher colors corresponding to larger cities; we see a clear stratification where larger cities have both lower slopes and lower intercepts. This indicates that smaller cities are more dependent on their urban centers while larger cities fragment into subcenters. An advantage of this method is that it lets us assign individual trips to components and examine the composition of them. We compute residents' exposure to different strata. We show 50% of intergroup interaction across cities comes from distal components, with implications for social contact given remote work trends; if centralized work declines, intergroup exposure may decrease.

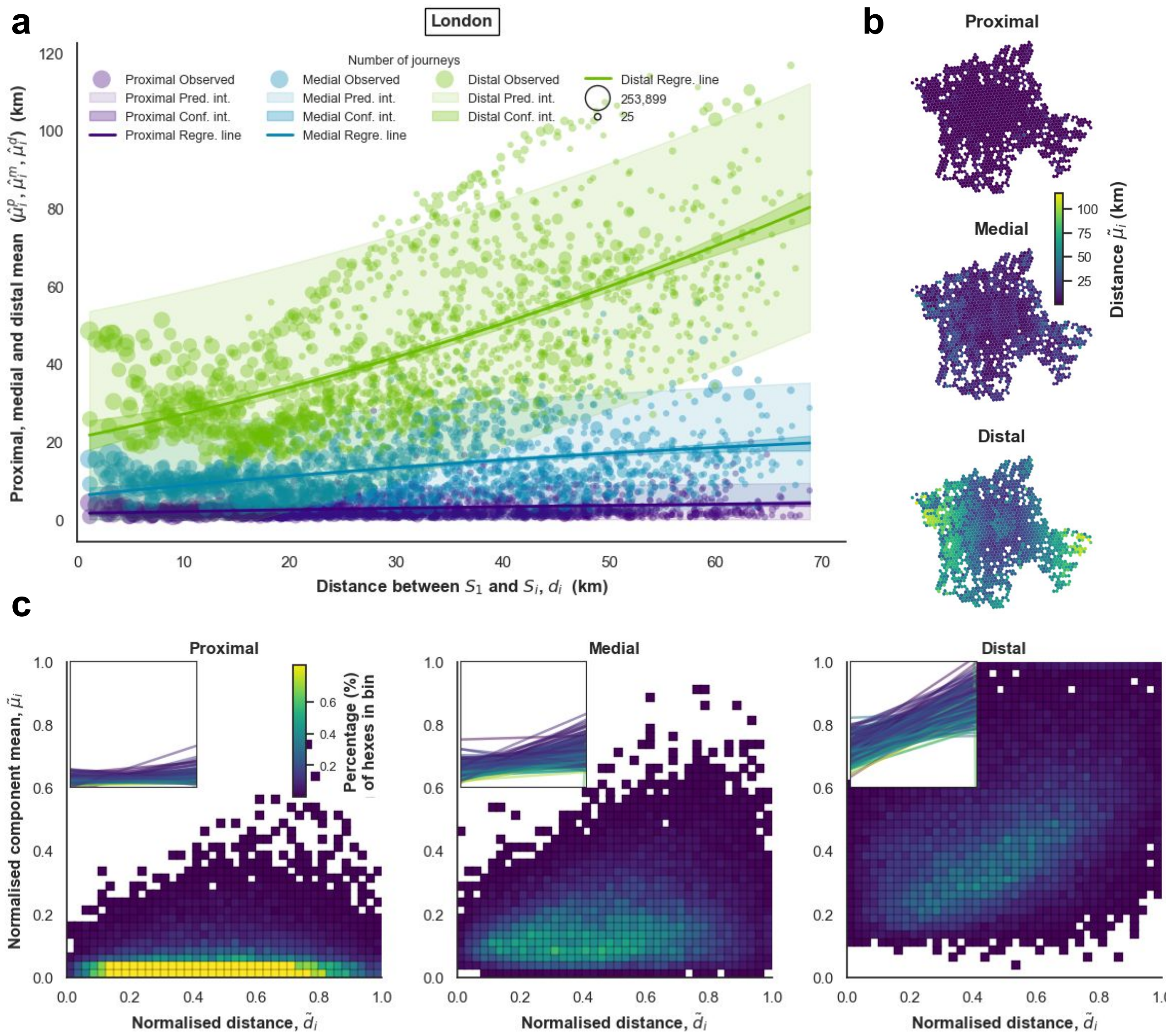

Figure 1: **a** London: component mean trip distance vs. distance to center—proximal $\approx$ flat; medial increases; distal increases most. **b** Maps of component means on a common scale; central areas still exhibit a distal component (outbound trips). **c** Pooled across 224 European cities: gradients steepen from proximal $\rightarrow$ distal and flatten with city size (insets: per-city fits), implying stronger central dependence in smaller cities and greater polycentricity in larger ones.