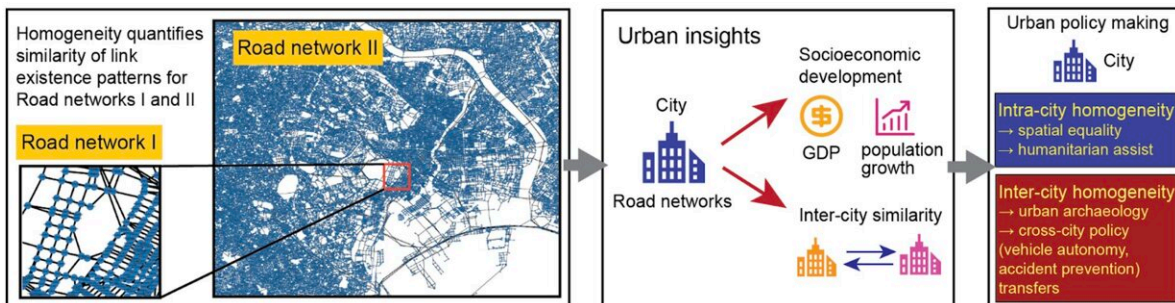


Using graph neural networks to measure the spatial homogeneity of road networks

May 9 2022, by Ingrid Fadelli



We develop the road network homogeneity to measure whether the part of the road network is similar to the entire network. Intracity homogeneity is strongly correlated with socioeconomic factors such as GDP and population growth. Intercity homogeneity reveals the directional urban similarity pattern from Europe to the United States and to Asia, which exactly aligns with the urban planning history. Credit: *Nature Machine Intelligence* (2022). DOI: 10.1038/s42256-022-00462-y

Researchers at Purdue University and Peking University have recently carried out a study aimed at better understanding road networks in cities worldwide using machine-learning tools. Their paper, published in *Nature Machine Intelligence*, outlines the results of an in-depth, data-driven analysis of road map-related data captured in 30 cities worldwide.

"Urban road networks (URNs) serve as the economic engine of a city and are shaped by multiple socio-economic factors (including population, economy) and urban development history," Dr. Satish V. Ukkusuri and Dr. Jianzhu Ma, two of the researchers who carried out the study, told TechXplore. "They play a central role in human mobility, good movement, biological virus spreading, and pollution generation. However, traditional road network metrics based on simple measures only provide a coarse characterization of URNs."

Past studies suggest that there are a series of patterns in the spatial homogeneity of URNs. These patterns could be captured using graph [neural networks](#) (GNNs), advanced graph-based machine learning tools that are often used in computer vision and natural language processing applications.

A key advantage of GNNs is that they can learn network representations by analyzing very large amounts of data. In their paper, Ukkusuri, Ma and their colleagues specifically used GNNs to analyze over 11,790 URNs in 30 cities worldwide, with the aim of predicting a new metric, dubbed network homogeneity.

"Many urban planners have analyzed cities using case-by-case approaches that study each city in isolation," Ukkusuri and Ma explained. "However, the quantitative comparisons of the urban environment across different cities using global data are limited. We wanted to utilize the power of our machine learning method and the information from massive data to understand the urban system in a global manner, including cities from either developed countries or developing countries."

Ukkusuri, a Reilly Professor of Civil Engineering at Purdue University, has been conducting research focusing on transportation system modeling, urban network analysis, and transportation sustainability for

two decades. Ma, on the other hand, is an associate professor at Peking University who has been exploring the potential of graph-based machine learning in multiple fields, including biology.

"Our common interest in URNs and past research experience on GNNs is what drove our team to explore the road network homogeneity over the last year," Ukkusuri and Ma said.

"The primary objective is to mine fine-grained road network information and present its connections with intracity development and intercity urban similarity."

Before conducting their analyses, the researchers divided all the URNs in their dataset into two parts: the "hidden region" and "observed region." Subsequently, they specifically trained the GNNs to learn the structure patterns of the road networks in the observed regions, so that they could then predict the structure of the network in the hidden region.

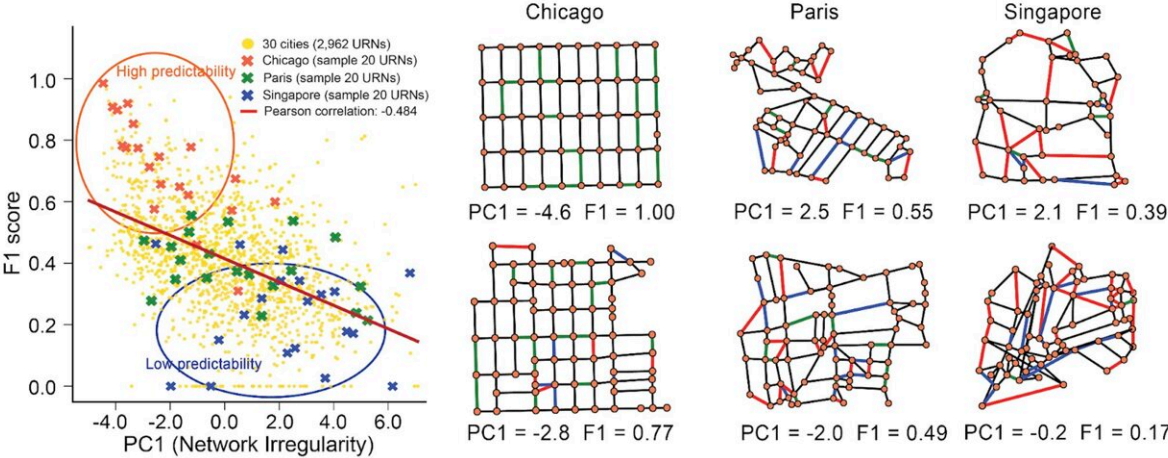
In their paper, Ukkusuri and Ma defined the metric they investigated, "network homogeneity," as the F1 score of the model's performance in predicting the hidden region in the URN data. F1 scores represent the precision and recall accuracy of classifiers or machine learning methods.

In the context of the team's study, a higher F1 score implied that the model was likely to accurately infer the hidden region from the observed region. It thus also signified a higher homogeneity of URNs.

"Our network homogeneity metric quantifies the intracity and intercity similarity of URNs. The intracity similarity is perceived by moving agents via daily activities unconsciously, and by [urban planners](#) via professional examinations qualitatively," Ukkusuri and Ma said.

"Besides, humans have characterized the intercity similarity long ago, when they called Budapest or Shanghai the 'Paris of the East.' Progress from qualitative evaluation to quantitative measure enables us to efficiently record, compare and predict urban evolutions in a standard manner."

The evolution of road networks in big cities are typically guided by top-down urban planning policies. The graph neural network-based model and the metric introduced by Ukkusuri, Ma, and their colleagues could help to evaluate and compare some of these policies.



We define the road network homogeneity as the F1 score of the link prediction task. We find the F1 score shares a negative relation with PC1 (network irregularity), suggesting that regular URNs are more likely to be homogeneous. The real-world links and predicted links in two URNs for three cities. Green links denote true positive (links exist in both reality and in predictions), red links denote false positive (links exist in predictions but not in reality) and blue links denote false negative (links exist in reality but not in predictions). Credit: *Nature Machine Intelligence* (2022). DOI: 10.1038/s42256-022-00462-y

"In China, a common slogan during urbanization is: 'consistently follow a blueprint' (Chinese: 坚持一张蓝图绘到底), which implies that urban stakeholders need to stick to a constant urban planning policy for a long period," Ukkusuri and Ma explained. "Urban planners could use the homogeneity metric we proposed to measure the similarity of URNs built at different ages and finally verify the temporal consistency of urban constructions within the period."

In addition to introducing a metric that could aid the evaluation of urban planning policies, the researchers' study unveiled connections between URNs, a country's gross domestic product, and population growth. The results they collected confirm the close link between human activities and urban environments.

"The insights from our study enable us to understand the complicated interplay between multiple factors in the urban system," Ukkusuri and Ma. "The unique feature of our work is that we bridge machine learning with urban science: the F1 score is a standard measure in machine learning, and homogeneity characterizes the network structure of URNs."

Ukkusuri, Ma and their colleagues were the first to investigate whether URN systems can be analyzed by machine learning models in meaningful ways. Their findings suggest that advanced machine learning models could be used to extract rich information related to socio-economic factors and the evolution of cities over time.

"Imagine when you walk around the corner of a street, sometimes you can even predict what the next block looks like simply based on the neighborhood you just pass," Ukkusuri and Ma said. "When you are driving in a city you have never been to, sometimes you feel very familiar with the surrounding area and feel it is just like another city you know. This could happen either in different cities in the same country or

across multiple countries. It is surprising that this phenomenon is not random and could be largely determined by simple factors such as intracity and intercity homogeneity, and trace back to the urban planning culture from Europe to North America and Asia, from ancient cities to modern cities."

The graph neural networks developed by this team of researchers could ultimately be used in different countries worldwide to measure the similarities between cities, evaluate urban policies and summarize urban activities. Remarkably, the model introduced in the recent paper could also be extended, both to analyze larger urban areas and to examine changes over longer periods of time.

"Other researchers can investigate road networks in cities from different continents, of different sizes, while our study takes 30 large cities as an example," Ukkusuri and Ma said. "Besides, they can measure and compare the homogeneity of a road network at different ages of history. Beyond road networks, the homogeneity theories of street views, [land use](#), and other infrastructure networks could also be established. There is much more opportunity to find more deep insights into complex urban systems."

The team's recent study is one of the first that try to apply state-of-the-art graph neural networks in the study of URNs. In their next studies, the researchers would like to develop their model further and apply it to more data, to collect more information about the homogeneity of URNs. Currently, they are conducting a study examining URNs and their links to specific socioeconomic factors.

In the future, Ukkusuri, Ma and their colleagues would also like to investigate the historical evolution of URN homogeneity. To do this, they will use time-series data collected in numerous cities worldwide and a more sophisticated neural network model.

"We are inspired by a study on structural invariants of URNs in Paris from 1790 to 1999 (Kirkley, A., Barbosa, H., Barthelemy, M., & Ghoshal, G., 2018)," Ukkusuri and Ma said. "From the betweenness centrality in street networks to structural invariants in random planar graphs, we hope to investigate the homogeneity properties for a wide range of cities at the history scale, from modern cities with complete data to ancient cities with limited data, such as Machu Picchu in the Inca Empire during the 15th century."

In addition to using machine learning models to examine the development of URNs over time, the researchers would like to use it to examine other types of data collected in urban environments. For instance, they would like to simultaneously analyze street view images, mobility interactions and internet browsing data, to identify more complex patterns that influence human lives in urban settings. For instance, this could help to better understand issues related to social equality and regional poverty.

"Road network data is simple and relatively stable, which is suitable to start our analysis," Ukkusuri and Ma said. "We are currently working with Internet companies in Japan to explore the human-urban environment system using big data and machine-learning techniques."

Finally, the researchers would like to conduct more studies investigating the general potential of AI in the field of urban science. Their work could also inspire other research groups to apply machine learning in the field of urban science, which could lead to interesting discoveries about the history and development of cities worldwide.

"We realized that AI paves a new way to learn the underlying signatures present in cities and how they can be used to make cities more efficient and sustainable," Ukkusuri and Ma added. "Besides, we realize much attention needs to be paid to avoid misusing AI without domain

knowledge in urban science. We will continue to explore the intersections of AI and urban science problems and hope to contribute to the interdisciplinary research community."

More information: Jiawei Xue et al, Quantifying the spatial homogeneity of urban road networks via graph neural networks, *Nature Machine Intelligence* (2022). [DOI: 10.1038/s42256-022-00462-y](https://doi.org/10.1038/s42256-022-00462-y)

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