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Urban access across the globe: an international comparison of different transport modes

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Access (the ease of reaching valued destinations) is underpinned by land use and transport infrastructure. The importance of access in transport, sustainability, and urban economics is increasingly recognized. In particular, access provides a universal unit of measurement to examine cities for the efficiency of transport and land-use systems. This paper examines the relationship between population-weighted access and metropolitan population in global metropolitan areas (cities) using 30-min cumulative access to jobs for 4 different modes of transport; 117 cities from 16 countries and 6 continents are included. Sprawling development with the intensive road network in American cities produces modest automobile access relative to their sizes, but American cities lag behind globally in transit and walking access; Australian and Canadian cities have lower automobile access, but better transit access than American cities; combining compact development with an intensive network produces the highest access in Chinese and European cities for their sizes. Hence density and mobility co-produce better access. This paper finds access to jobs increases with populations sublinearly, so doubling the metropolitan population results in less than double access to jobs. The relationship between population and access characterizes regions, countries, and cities, and significant similarities exist between cities from the same country.

INTRODUCTION

Cities exist to enable people to easily reach other people, goods, and services. This is achieved through transport networks, which move people across space faster, and land-use patterns, which distribute people, goods, and services across space. Access (or "accessibility") is the ease of reaching those valued destinations, and thus is a critical measure of urban efficiency. Higher land use density and travel speeds correspond with greater access[1]. Urban population size has been associated with greater productivity and creativity, a centerpiece of the urban economies of agglomeration literature[2,3]. This paper measures how access varies with metropolitan population size, whether larger cities also enjoy increasing accessibility, which we expect will affect how well population produces economies of agglomeration.

To measure access across the globe, we use the cumulative number of job opportunities reachable under a predefined travel time threshold. Since jobs are places of interaction, that provide service either directly or indirectly to customers, jobs are a key indicator of "urban opportunities"[4] serving both as employment opportunities, and as urban amenities.

The role of access in transport, sustainability, and urban economics is increasingly recognized. The positive correlation between access and land value originates from the trade-off between time (transport cost) and space (the price of land)[5–7], and this positive correlation has been shown with various hedonic models in different contexts[8–10]. Access affects firm location choice[11], development probability of vacant land[12], commute mode choice[13,14], and transport emissions[15]. The expansion and

rapid growth of urban areas call for a meaningful measure of geographical connectivity, to which a measure of access to job opportunities can be a useful tool[16].

Cities have been ranked and recognized by economic and demographic statistics that describe their sizes and productivity[17–20]. The efficiency of transport infrastructure and land use in linking people with opportunities is also a vital measure for cities[21–23], and its significance is on par with economic and demographic measures. However, there has been no previous large-scale, multi-modal comparison of access to jobs for cities across the globe. Cities differ in the levels of transport infrastructure and development patterns. On the one hand, US cities prioritize mobility over density; the density of US cities are relatively low[24] due to sprawling development patterns. Road length per vehicle is higher in the US than in Europe, Canada, and Oceania[25]. On the other hand, European cities are compact and have a denser road network than US, Canadian, and Oceania cities[25]. These differences among cities and global regions would have accessibility implications, that affect the quality of the transport system within each city. This paper examines the type of development pattern most conducive to accessibility, and whether mobility and density can co-exist for better accessibility.

Understanding global urbanization and transport development are needed[26]. The quantification of access using cumulative opportunities provides a universal unit of measurement for transport and land use, and the opportunity for defining cities by transport and land use with a uniform benchmark. Measuring accessibility sheds light on the basic structure of cities

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underpinning economic efficiency, and reveals where a city (i.e., metropolitan area) stands relative to its overall size and other attributes, and relative to other cities.

Access has been measured and compared domestically in the United States[27], Australia[28], Brazil[29], Canada[30], New Zealand[31], and in European countries[32] using the cumulative opportunities measure. One notable advantage of the cumulative opportunities measure is being in absolute and comparable units[33], and having clarity of meaning, and being an easily understood and interpretable concept[34]. This paper uses a travel time threshold of 30 min that is consistent with many estimates of one-way travel time budgets to work, to measure access to jobs in all cities[35–39].

This paper compares access globally and covers access by automobile, transit, walking, and cycling where data were available. We examine patterns in the relationship between access and populations, and whether cities cluster by their global region. This work also examines whether the disparity in access to jobs between modes of transport is linked with population size. Access to jobs data in this global comparison are collected by different researchers and organizations. The population provides a consistent measure of metropolitan area size that is comparable across global regions. This paper details the data collected from multiple agencies in the supplementary information, commenting on differences in data sources. Access measures for each model are tabulated and cities ranked by the total population in the supplementary information. The paper examines access in global cities across modes, across countries, and across cities.

RESULTS

Comparison across countries: scaling city-level access with population

In order to compare accessibility across cities worldwide, we first compare the relationship between the population size and accessibility in different countries. Such comparison can help clarify the differences in the relationship, and in the returns to scale of metropolitan population size on accessibility between different countries, i.e., is the increase in access proportional to the increase in population in each country, and how different countries compare.

We use scaling functions to quantitatively measure the relationship between population and the level of access to jobs. The formulation of the scaling function is shown in the methods sections. The scaling coefficient (β_1) signifies the returns to scale, where $\beta_1 > 1$ means doubling the metropolitan population will more than double the level of access. We find the city-level access to jobs increases with population. Table 1 shows the model fit and coefficients.

Although the relationship between access and population, in general, is positive, with larger cities exhibiting higher accessibility by all modes than their smaller counterparts within the same counties (the β_1 coefficients are positive), we generally see

diminishing returns in access with respect to population (the coefficient is less than one), so we have sublinear scaling, meaning population rises faster than access. Notably, transit in Chinese cities is the only exception to the sublinear scaling: the increasing population in Chinese cities confers proportionally more accessible jobs.

Comparison across modes

We compare city-level access to jobs by four modes of transport: automobile, transit, walking, and cycling. The population and access by different modes on a logarithm scale are plotted in Fig. 1 through Fig. 4; scaling functions are fitted as trend lines. Figures showing the accessibility by different modes of transport for each country is provided in the Supplementary Information. Cities above the trend lines are overperforming based on their mode and country category; cities beneath the trend lines are underperforming. Our comparison corroborates that differences in structure exist both within, and between, global regions. Although cities of the same global region tend to share similar trends in access, cities from different global regions can cluster on access attributes.

Walking access to jobs is shown in Fig. 1. Walking is part of every other mode of transport. The walking access alone represents the spatial distribution of population relative to urban opportunities. Urban density, the proximity between residential and employment centers[40], and mixed land use increase walking access.

For any given population, Chinese and European cities have markedly higher walking access to jobs than cities in other countries. American cities, with their lower densities and auto-orientation, as well as the functional separation between residential and employment districts, have the lowest walking access to jobs globally. Among American cities, New York and San Francisco-Oakland (excluding San Jose) are more similar to European cities than to other American cities. In Oceania, Wellington also clusters amongst European cities with significant walking access to jobs, and Sydney comes close to European access levels.

Cycling access is shown in Fig. 2. Cycling access in major cities tends to be below automobile, but higher than transit. Chinese and European cities generally have greater cycling access than the US cities with similar population sizes. Cycling access in Oceania cities is comparable to the best American and Brazilian cities, but lower than Chinese and European cities.

Cycling provides better access to jobs than transit in every city where access data of the two modes are available. Cycling has no waiting or transfers time penalties, and cycling routes to and from destinations are less circuitous than transit. Cycling provides better access than automobiles in the city of Shanghai, where congestion reduces access by automobile.

Table 1. Coefficients and model fit for the scaling models between city-level access and population											
	Automobile			Transit			Walking			Cycling		
Nationality	β_0	β_1	R^2	β_0	β_1	R^2	β_0	β_1	R^2	β_0	β_1	R^2
Brazil	–	–	–	1.17×10^6	−0.23*	0.00	24.30	0.41	0.36	103.53	0.45	0.37
Canada	1.31×10^4	0.18	0.40	204.54	0.35	0.34	–	–	–	–	–	–
China	102.58	0.65	0.82	3.90×10^{-6}	1.57	0.40	0.087	0.89	0.19	12.99	0.71	0.24
Europe	1.98×10^4	0.28	0.00	10.54	0.66	0.67	115.95	0.41	0.58	105.69	0.56	0.63
Oceania	146.69	0.52	0.84	50.06	0.47	0.75	59.92	0.36	0.56	113.02	0.46	0.74
United States	1.68×10^3	0.39	0.54	0.08	0.80	0.39	1.69	0.54	0.36	21.24	0.54	0.49

*With only 4 Brazilian cities available, the scaling coefficient for Brazilian transit inconclusively negative.
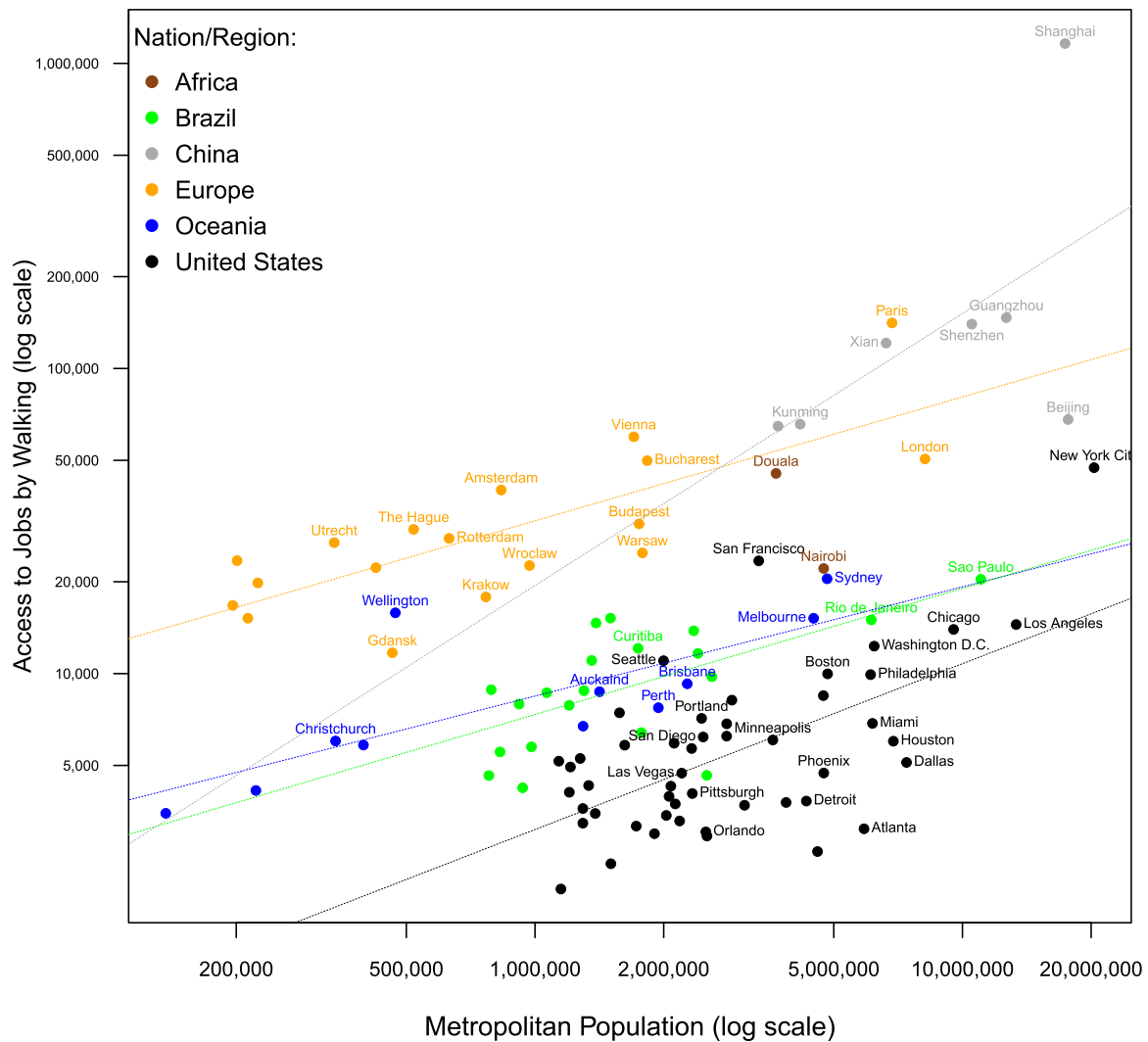**Africa not included due to the small sample size.

Fig. 1 Walking access to jobs and metropolitan population.

Transit access is plotted against the population in Fig. 3. Transit service provision is linked to patronage in a positive feedback system[41], which affects transit performance, so more populous cities with a greater base for transit patronage tend to have better transit quality of service, with higher frequency, shorter access distances, and more direct service, resulting in higher access to jobs[42].

Chinese and European cities have higher transit accessibility than the others. London and Paris have a longer history than North American cities and were well developed before the advent of the automobile. It is expected that these European cities would better support transit and walking. Australian and Canadian cities are similar in terms of transit access, with the exception of Quebec City, which, despite its age, more resembles American cities. Brazil's largest metropolises, São Paulo and Rio de Janeiro have much lower accessibility levels than what would be expected for their population. This is in part because these two cities have large territories with low population densities coupled with a high concentration of jobs in the city center, and both cities have relatively poor transport conditions with some of the highest average commute times among global cities[43].

The majority of American cities lag behind in transit access for their population size. New York and San Francisco-Oakland are exceptions for the American cities, with high transit access relative to size. Metropolitan Washington, Boston, Philadelphia,

Chicago, and Seattle bear more resemblance to Australian and Canadian cities than to other American cities, although transit access for these cities is still lower than their Australian and Canadian counterparts. The two African cities, Douala and Nairobi both have better walking and transit access than average American cities.

Automobile access is plotted in Fig. 4. Large cities tend to have well-developed road networks and have employment opportunities proportional to the population sizes, which, generally translates to greater automobile access. Conversely, heavy traffic flows can cause delays in large cities, especially during peak hours when automobile travel time data for this study are measured.

Both globally and within each nation, automobile access increases with population. Chinese and European cities follow a distinct trend from other global cities and have the highest automobile access for each population level. American cities have greater automobile access than Australian and Canadian cities at each level of population. Historically the United States has placed heavy emphasis on auto-mobility, and the Interstate highway system created by the Federal-Aid Highway Act of 1956[44] greatly facilitates movement by automobile both within and between metropolises. New York has high automobile access, but its level did not grow out of proportion to make New York an outlier; New York is an outlier among US cities for high walking and transit access. Oceania and Canadian cities are comparable to American cities that are in the lower quantile of
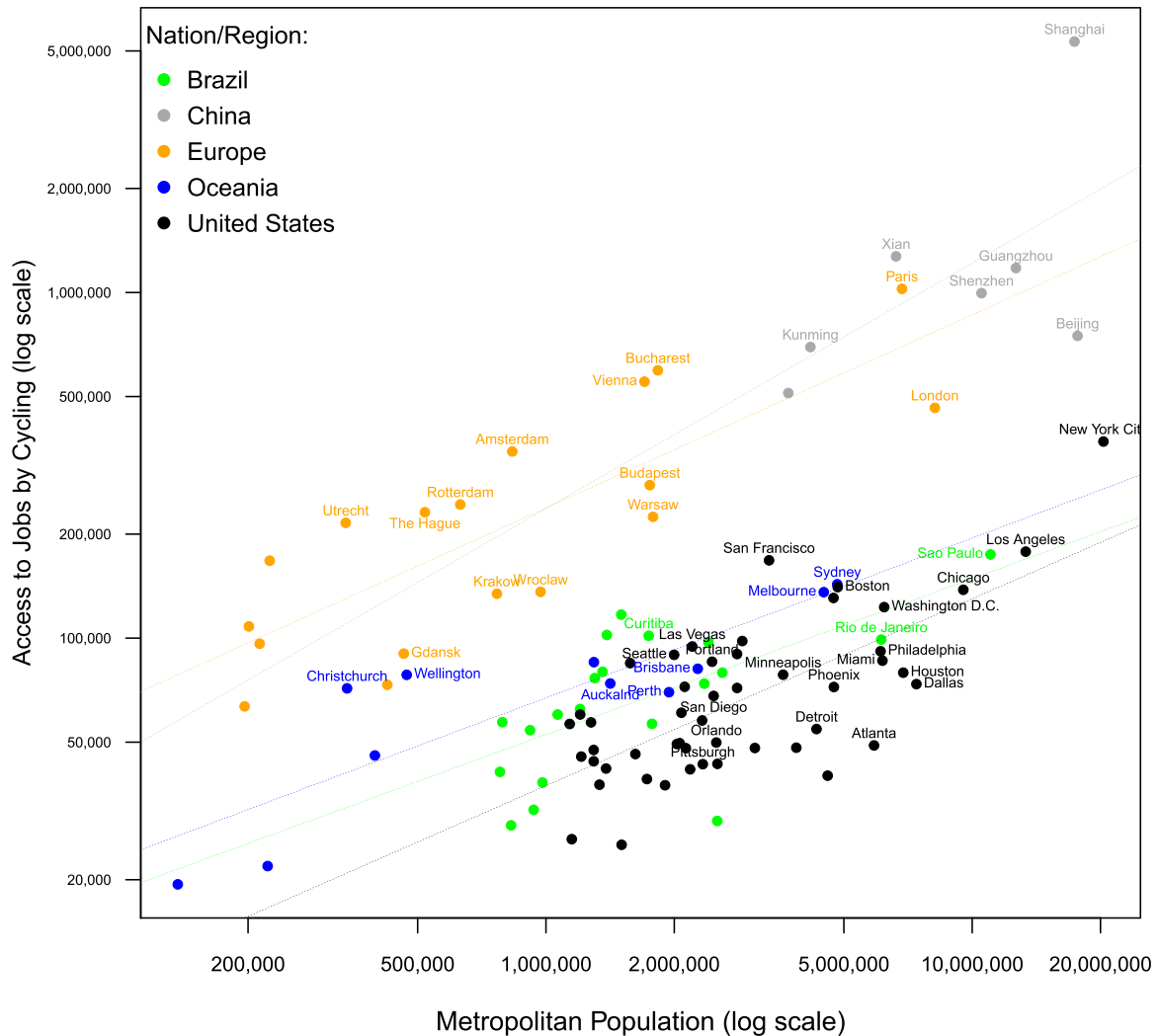
Fig. 2 Cycling access to jobs and metropolitan population.

automobile access; Perth more resembles mid-tier American cities at its size.

Comparison across cities: access with populations

Across cities, we find population correlates with access to job opportunities. People in more populous cities generally have better accessibility. Population reflects the need for transport. On the one hand, it is hypothesized that larger metropolitan areas enjoy economies of agglomeration and tend to have better public transport systems and higher residential and employment densities, thus better access. On the other hand, congestion in large cities reduces access, and differences in urban networks and spatial configuration can result in varying levels of access for cities with similar sizes. Similarly, as the population increases, urban densities rise slower than the population, as some of the additional growth expands urban territory, and thus distances required[45]. In the Supplementary Information, we tabulate global cities by the access of different transport modes (where data were available).

The correlation between population and accessibility of different modes is strongest with the automobile (0.69), followed by cycling (0.55), walking (0.48), and transit (0.44). An automobile can generally reach more territory than other modes within a 30-min threshold, so the automobile accessibility relates more strongly with the metropolitan population than other modes.

The weaker correlation for the transit mode is largely due to transit being the most susceptible mode to variations in service provision, and urban land use. Small cities with good transit infrastructure can provide similar levels of access to jobs within 30 min as many large cities (which may have more jobs available for longer time thresholds, which are less valuable to residents than nearer jobs). Examples of such small but compact cities with good transit services include most European cities, and Wellington and Christchurch in New Zealand, which have relatively good transit accessibility for their sizes. Large and densely populated metropolitan areas such as New York, London, and Paris have good transit accessibility.

Modal comparison: transit as a benchmark

We explicitly examine the disparity in access provided by different modes of transport from different cities, using transit as the benchmark. The existence and extent of such disparity vary by city, and by the country of the cities[46]. The difference in access by different modes is compared using the ratio of cumulative access so that the difference between modes is scalable. Since the access data from each city is collected by the same source and over the identical geographical extent, the ratio of access by mode provides a reliable gauge for comparing the within-city modal difference. Figure 5 shows the ratio of 30-min access to jobs by automobile and by cycling, relative to the transit mode.
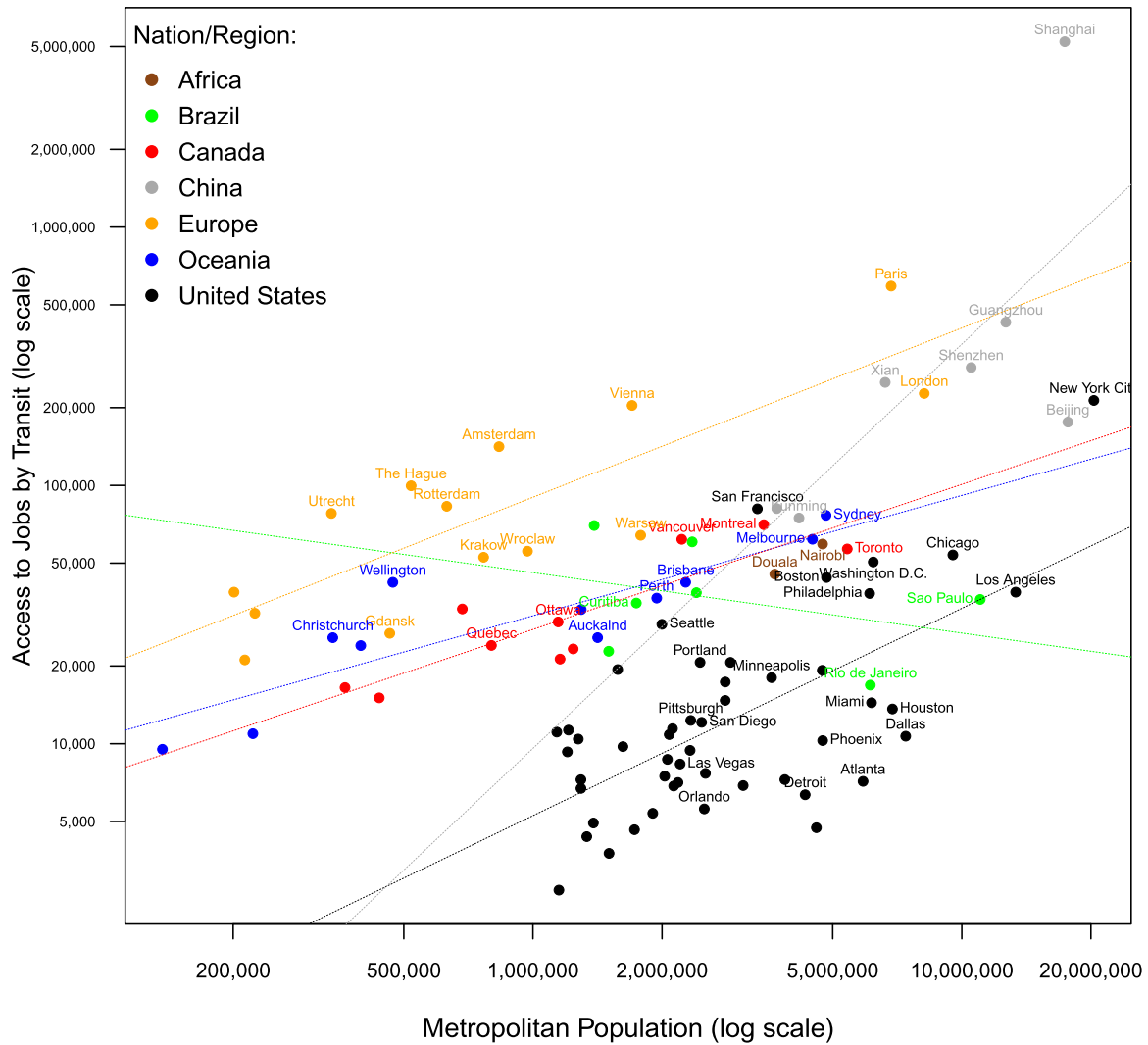
Fig. 3 Transit access to jobs and metropolitan population.

The automobile provides better access than transit in all cities we compared, except in Shanghai, China, where automobile reaches about 90% of the jobs reachable by transit at 30 min. The disparity between transit and automobile access is greatest in American cities; Oceania and Canadian cities have more comparable levels of access between the two modes, although the gap remains significant. Among the Oceania cities, Perth and Wellington are the two extremes (outliers) for respectively having the largest and smallest gaps between transit and automobile access to jobs.

Transit and automobile often have the highest commute mode share in major cities. Income[47] and physical ability affect mode choice, so the relative level of access to jobs provided by automobile and transit has equity implications[48]. The ratio of the automobile to transit access correlates weakly with population ($R = 0.10$), so larger populations reduce the gap between transit and automobile, but generally do not guard against inequitable transit access to jobs. US cities with better transit access tend also to have lower auto to transit access ratio; examples include New York, San Francisco-Oakland, Washington, and Boston.

The automobile provides better access than transit in almost all cities we compared. The disparity between transit and automobile access is greatest in American cities Fig. 5; Australian and Canadian cities have more comparable levels of access between the two modes. The ratio of the automobile to transit access does not seem to be affected by the population.

All cities we examined have cycling access higher than that of transit. Oceania and European cities have stable ratios of cycling to transit access, where cycling can reach about twice as many jobs as transit. The gap between cycling and transit access to jobs is larger in the US and Chinese cities. The ratio of cycling to transit accessibility has a weak correlation with populations ($R = 0.17$), so the gaps between transit and cycling are smaller with larger populations.

DISCUSSION

This research conducts a systematic, multi-modal, international comparison of access to jobs, which is the core variable connecting transport networks and land use, and the central factor in characterizing cities and explaining why cities exist[49]. This paper compares the performance of the transport and land-use system across cities.

One notable finding of this paper is the national difference in the relationship between access and population. While outliers exist, there are remarkable similarities for cities in the same global region. We find mobility and density can co-exist and collectively co-produce greater access to jobs for a metropolitan area. Sprawling development accompanied by an intensive road
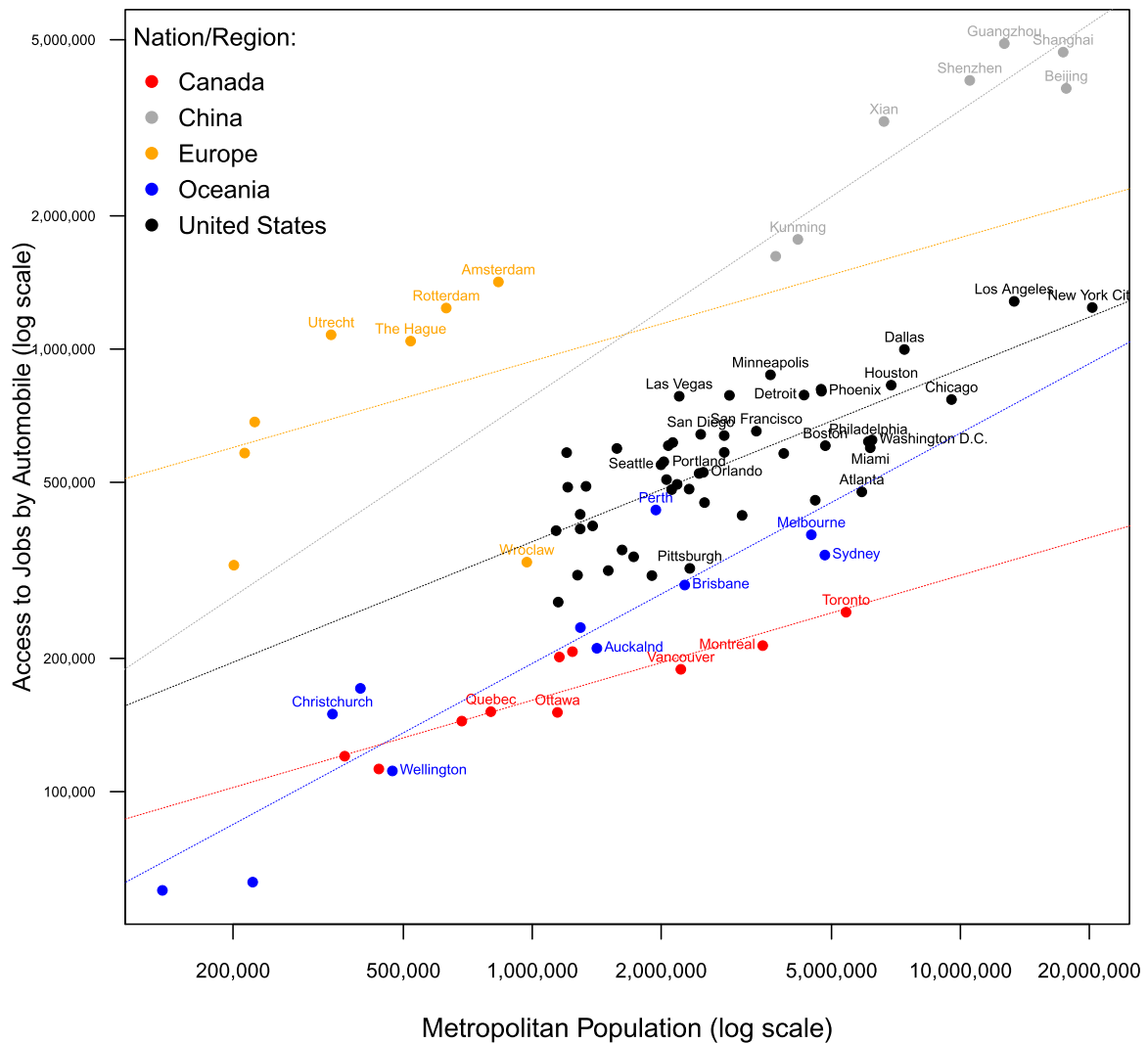
Fig. 4 Automobile access to jobs and metropolitan population.

network, as is common in American cities, results in modest automobile access, but low access for transit and active modes of transport. Oceania and Canadian cities, with US-style land, uses but without US-level freeway networks have relatively low automobile access and are generally situated between American and European cities in transit and walking. This is consistent with previous findings[23]. Chinese and European cities are compact, and well supported by road networks, resulting in the highest accessibility in all modes of transport.

While it is unsurprising that this paper finds city-level access increases with population, the relationship is neither linear nor constant across countries. Access does not increase proportionally with a population (for all modes in all countries where data are available, except transit in China), and presents diminishing returns to scale, so the doubling of city population will likely less than double access to jobs.

More populous cities present more available urban opportunities, usually at higher densities, with higher levels of traffic congestion and better public transport infrastructure. When appropriately matched with transport infrastructure, compact urban development generally improves access to jobs, despite increased congestion. In terms of the disparity between modes of transport, we find larger cities tend to narrow the gap between transit and automobile access to jobs. The disparity between transit and automobile is most significant in the US, mostly as a

result of sprawling development, which increases automobile speeds and makes transit service more difficult.

Two major caveats are identified: the demarcation of city boundaries, and the jobs and population data source. The modifiable areal unit problem is present in defining the city boundary for analysis, for example, excluding lower-density outlying (exurban) areas likely inflates the access measure. Although there is no consistent standard for defining city boundaries across nations, the geographical area was chosen for measuring access generally reflects what would be considered the built-up, urbanized area in each city that envelops commute ties to the urban core. This city boundary issue is further alleviated by using the population-weighted access measure, where the population data were available. The second caveat involves the census data on jobs and population numbers collected (or not) by governments of different nations, that vary in accuracy and coverage. We believe that while more consistent standardization of city boundary measurement and employment definition would affect specific numbers, they would not substantially change the general findings and conclusions from this study. By definition in some sense, "informal economy" jobs are excluded in all countries (which underestimates access in some metropolitan areas much more than others), however, the magnitude of this is unclear by its very nature.
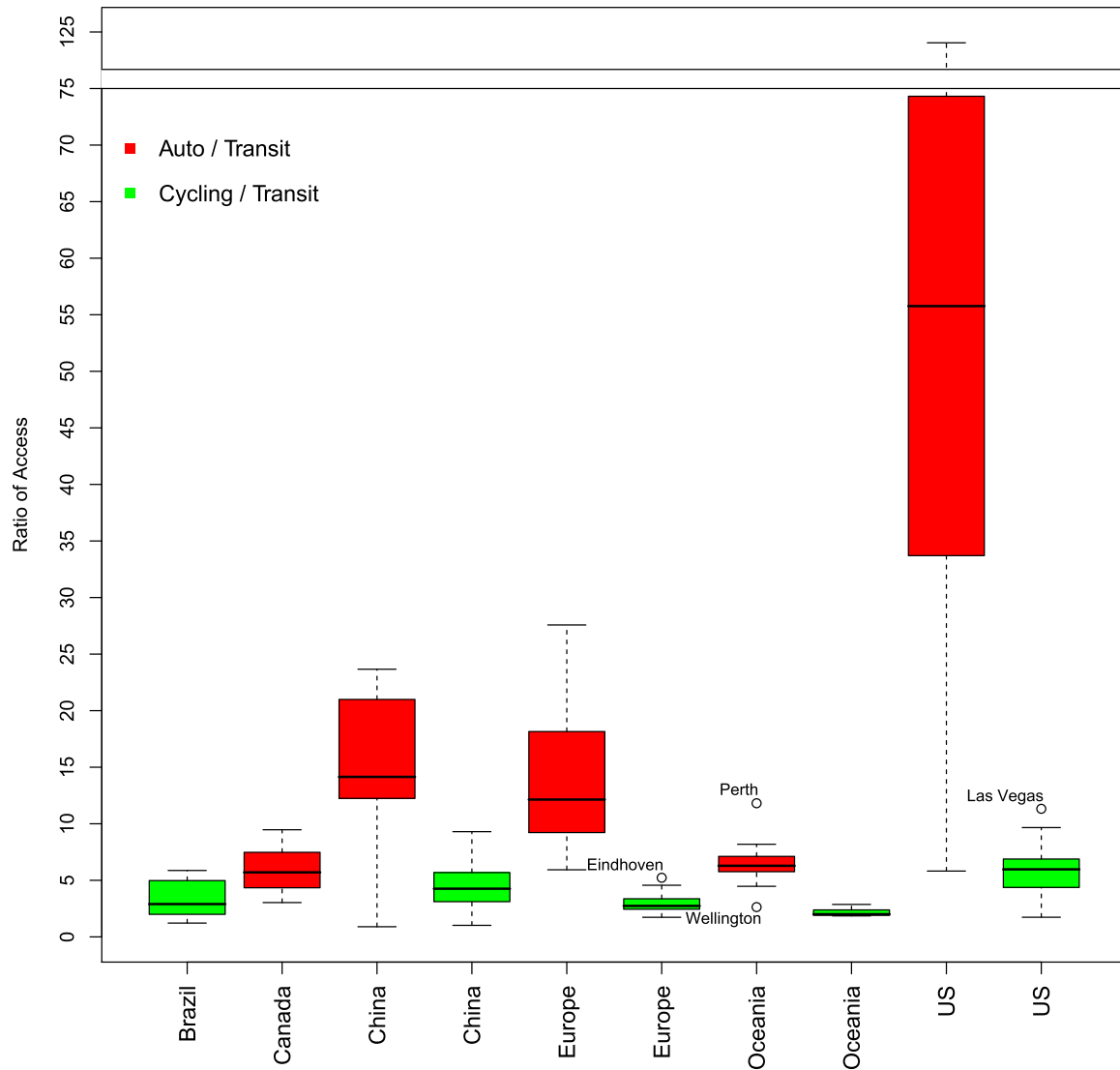
Fig. 5   Ratio of automobile to transit access (red), cycling to transit access (green). Boxes span 25th to 75th percentile, whiskers extend to max/min of the values, excluding outliers (>1.5 box heights away from box edges, which are shown as circles).

This work provides a cross-sectional comparison of cities, focusing on how cities of similar scales compare, in terms of the coupling between transport infrastructure and land use, measured by access. Future research can link access with other city-level characteristics, including income, GDP per capita, transport emissions, and commute duration, to shed light on the interplay between these elements. In the future, it will also be possible to explore time-series data on access across the globe, to observe the longitudinal trend in the co-evolution of access with other urban elements.

METHODS

Method for measuring accessibility
Access is calculated as the cumulative number of jobs reachable under a 30-min travel time threshold. Equation (1) specifies the cumulative access measure, for a location of interest. The concept of cumulative opportunities can be conceived graphically as the geographical area covered within a travel time threshold, and the number of opportunities contained in that area.

Selection of travel time threshold affects the access measure[50,51]; although distance decay functions[52] (time-weighted cumulative opportunities[53]) can be used to avoid the choice of thresholds, the difference in

data sources and variations across geographies, as well as different preferences for travel between people in different cities, prevent the use of a consistent decay function. We use a 30-minute threshold without distance decay (Eq. (2)) for consistent comparison across modes.

$$A_{i,m} = \sum_{j=1}^{J} O_j f(C_{ij,m}) \tag{1}$$

$$f(C_{ij,m}) = \begin{cases} 1 & \text{if } C_{ij,m} \\ 0 & \text{if } C_{ij,m} \geq t \end{cases} \tag{2}$$

where, $A_{i,m}$ is access measure for zone i, by mode m; O_j number of jobs at zone j; $f(C_{ij,m})$ is the travel time between zone i and j for mode m; t is the travel time threshold $= 30$ min.

Access measures for individual zones are aggregated to produce city-level averages. Person-weighted city averages are used where the population data were available, and the population of each subdivision is used as a weight. For the US, Australian, Chinese, and Polish cities, the working population is used as a weight; the total population is used as a weight for Brazilian, Canadian cities, Paris, and London. City-level access of African and Dutch cities are arithmetic averages of subdivisions and not weighted by population, and are thus expected to be lower than population-weighted measures for the same area. Equation (3) shows the formulation of population-weighted city-level access. This population-based weighting scheme reflects average access as experienced by the

entire population.

$$A_{l,m} = \frac{\sum_{j=1}^{J} p_j \times A_{j,m}}{\sum_{j=1}^{J} p_j} \quad (3)$$

where, $A_{l,m}$ is the city-level access for mode m in the city l; p_j is the population within zone j; and J is the number of zones within the city.

Accessibility data

Accessibility to jobs in each city is calculated based on the subdivision of the city into zones, the travel time between zones, and the number of jobs within each zone. Traffic[54] and transit schedules can cause temporal variations in access[55,56], so the level of access differs by hours of the day. Automobile accessibility is based on historical traffic data, and includes the effects of congestion; recurrent congestion is included for transit through the digitized transit schedule data; walking and cycling does not consider congestion and use all links where walking and cycling are legal, not only where they are pleasant. We measure access based on the morning peak travel time. A detailed description of data sources is provided in the Supplementary Information.

Pedestrians encounter both signalized intersections and non-signalized street crossings that add additional travel time, which is partially but incompletely accounted for by adjusting pedestrian walking speed, so walking access tends to be overestimated. Cycling access is calculated using all roads, although cyclists selectively use roads depending on vehicular speeds and levels of traffic for safety reasons, so actual access by cycling tends to be lower than estimates using all roads[57,58]. Digitized transit schedule information in general transit feed specification format (and a similar system in China) is used for calculating transit access. Transit travel time estimates cover transit station access, egress, waiting, and transfer time, and assumes perfect schedule adherence (on the theory that schedules have been calibrated to improve reported "on-time performance", but perfect adherence may result in overestimation compared with actual access). The automobile travel time includes the effect of congestion, but not searching for parking.

Scaling access to population

To quantitatively measure the proportionality between population and the level of access to jobs, we group cities by country and fit scaling models[59] (Eq. (4)) to cities of the same countries. The scaling coefficient (β_1) signifies the returns to scale.

$$A_{l,m} = \beta_0 P_l^{\beta_1} \quad (4)$$

where, β_0, β_1 is the coefficients of the scaling model.

DATA AVAILABILITY

The data generated and analyzed during this study are described in the following data record: https://doi.org/10.6084/m9.figshare.13476867[60]. The access data are openly available as part of the figshare metadata record in the file "AllCities.csv". A list of all cities included in the study, along with the sources of the data used for each city, is available in the file "SI for Urban Access Across the Globe—An International Comparison of Different Transport Modes.pdf". Both of these files are also available in PDF format via the Supplementary Information of this article.

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AUTHOR CONTRIBUTIONS

Study conception and design: D.L.; analysis and interpretation of results: H.W.; draft paper preparation: H.W.; accessibility calculation for respective nations/cities: H.W., P.A., G.B., C.B., A.E., J.H., T.K., B.M., M.N., R.P., J.P., A.S., and J.W. There is no difference in contribution between authors providing accessibility calculation for different nations/ cities. All authors reviewed the paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION