



# Tradeoffs in environmental and equity gains from job accessibility

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Increasing job accessibility is considered key to urban sustainability progress, both from an environmental and from a social perspective. However, sustainability outcomes depend on the processes contributing to accessibility trends, not just the trends themselves. Here, we ask whether sustainability benefits have followed from accessibility trends in the United States. We measure changes in accessibility from 2002 to 2014 across 909 US urban areas and decompose these changes to understand underlying infrastructure and land use processes. Our results show that job accessibility has increased across 74% of urban areas for the average resident, using both cars and transit. However, most of these accessibility gains were not achieved in ways that are inherently beneficial to environmental or social sustainability. In some urban areas, accessibility increases were conducive to reducing emissions, while in others, accessibility increases were conducive to reducing social inequities. However, accessibility increases almost never created a simultaneous social and environmental “win-win,” as is often assumed. Our findings highlight how the spatial patterns of urbanization create tradeoffs between different facets of sustainability. Identifying where social objectives take precedence over environmental objectives (or vice versa) could help determine how accessibility increases can be accomplished to contribute to a more sustainable urban future.

urban poor | transport | mobility | commuting | emissions

At its core, sustainability is about achieving a simultaneous “win-win”: meeting the needs of humans now while at the same time protecting the ecosystems that will support future generations (1, 2). Development is sustainable if the social and environmental systems that are so often in tension both prosper. By this definition, the need for sustainable development is particularly pronounced in urban areas. Urban areas contend with durable social inequities, which undermine the civic infrastructure of cities (3). They also produce the majority of carbon emissions which profoundly alter supporting ecosystems (4). Urban land changes that impact both equity and emissions simultaneously are a window into whether development can feasibly meet the win-win aspirations of sustainability.

Accessibility—how time effectively urban residents can reach places they want to go—is arguably the urban land characteristic with the strongest links to equity and emissions. Changes in accessibility, especially job access, have important equity and emissions impacts (5–7).

From an equity lens, job accessibility shapes the economic mobility of urban residents. Residents with higher accessibility to economic opportunities are more likely to be employed, to face shorter periods of unemployment, and to earn a higher income (8–10). In addition, residents with high accessibility spend less time and money commuting to work. Long expensive commutes are especially problematic for low-income residents, who spend a disproportionate percentage of their take-home pay on transportation (8.4%), more than double that of the median American family (11). Furthermore, since commuting happens daily, the costs of low accessibility are persistent and may have long-term effects that perpetuate economic disadvantage (10, 12).

From an emissions lens, job accessibility shapes daily commutes, which account for the majority of the 28% of total US greenhouse gas emissions spent on transportation (13). High accessibility can reduce fuel consumption and enable walking and cycling as feasible travel modes, both of which lessen urban emissions (4, 14, 15).

Given that high accessibility can be both an equity and an emissions boon, it is common to conclude that land changes that increase accessibility are a positive step toward satisfying the multipronged aims of sustainable development. However, to our knowledge, there are no empirical assessments that explore this hypothesis. It is known that not all access changes are created equal. Accessibility increases that distributionally benefit high-income residents over low-income residents can aggravate already existing inequities and therefore have less inherent social value. Accessibility increases that prioritize high-speed highway expansion over locating jobs and housing in close proximity can increase travel demand (16–18) and emissions and therefore have less inherent environmental value. Implicit in these arguments is the possibility that some accessibility increases have no sustainability value, benefiting neither disadvantaged populations nor the environment.

When have accessibility increases been a conduit for reducing economic inequity or emissions? Furthermore, under what conditions are these equity and emissions benefits co-occurring or mutually exclusive?

To answer these questions, we first measure trends in accessibility, constructing a 1-km grid gravity-based measure of job access (19) in all 909 micropolitan and metropolitan statistical

## Significance

Access to employment is key to the sustainability of urban areas. Although changes in access have consequences for multiple pillars of sustainability, in tandem, potential tradeoffs are rarely explored. This analysis measures employment accessibility trends over the past decade across and within US urban areas and assesses how these trends may be shaping emissions and social equity. We find that although US urban areas have increased in accessibility by 11% on average, few increases have provided both environmental and social value simultaneously. This study points to a paradox in sustainable development, where emissions mitigation and the welfare of low-income urban residents can be at odds.

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areas of the contiguous United States for 2002 and 2014. We choose metropolitan and micropolitan statistical areas as our geographic boundary since they are defined by a common commute shed. The gravity-based access measure takes, as inputs, the spatially explicit layout of road infrastructure (20) and transit and bus routes (21), housing distributions from block-level census counts (20, 22), and employment densities from the Longitudinal Employer–Household Dynamics Survey (LEHD-LODES) (23). The measure assumes that accessibility levels are directly proportional to the attractiveness of opportunities (measured by the number of jobs in each census block) and indirectly proportional to the time cost of reaching these jobs. By measuring accessibility at a high spatial resolution, we address recent calls to recognize the heterogeneous structure of cities (24) and move beyond arbitrarily chosen commute distance thresholds (25).

Once measured, we devise a way to characterize how accessibility changes affect our two key themes—equity and emissions. Equity and emissions impacts differ, depending on who has benefited from accessibility changes (i.e., low-income populations or average residents) and how accessibility has changed (i.e., through factors like job growth or loss, changes in the speed of travel, and changes in the proximity between jobs and workplaces). For instance, we posit that generally accessibility increases from speed effects have little to no inherently beneficial impact on emissions or equity (Fig. 1). For emissions, the expansion of high-speed road infrastructure generates additional vehicle miles traveled (VMT) in the range of 0.6–1.0 VMT per lane mile, substantially negating the emissions benefits of congestion relief (16, 26, 27). Highway investment also has been shown to contribute to decentralization and low-density growth (28). For equity, these development patterns make public transit and carpooling less viable—modes that are more than twice as often used by low-income populations (29).

In contrast, accessibility increases from proximity can more often lead to environmental and social gains, decreasing com-

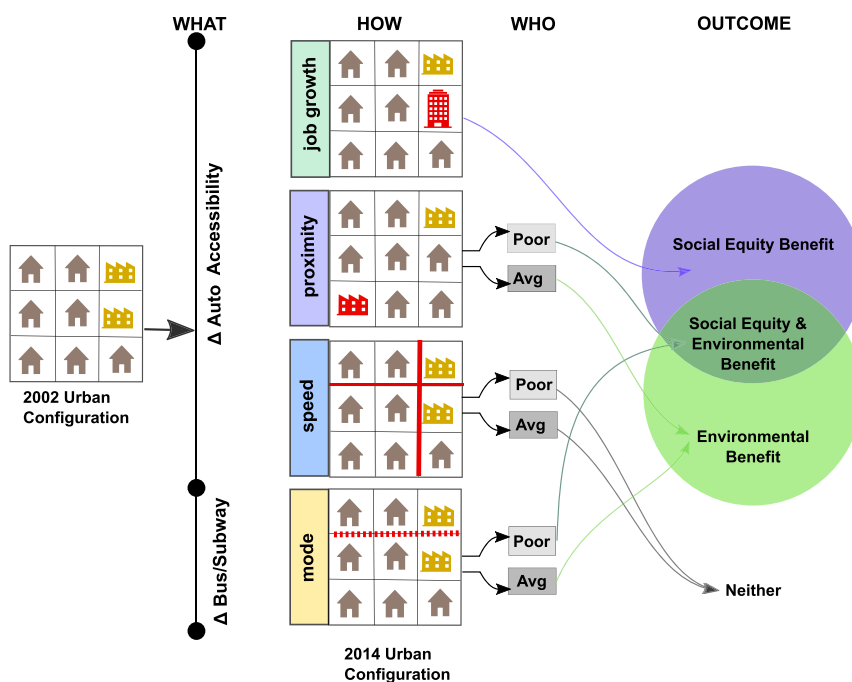
muting distances and increasing the viability of low-carbon, low-cost travel modes such as walking, biking, and transit (4, 15).

To isolate the contribution of job growth, job movement, and residential relocation to accessibility change, we use a counterfactual decomposition method (30). We calculate accessibility for a series of counterfactual scenarios, where residential locations (for all residents or for those living below the poverty line), job numbers, and job locations are held constant between 2002 and 2014. To determine the contribution of highway travel to accessibility estimates, we also create a counterfactual scenario where all urban roads are traversed at 30 mph, the speed limit of most local secondary roads, instead of at their actual speed limits. By comparing observed accessibility estimates to these counterfactual scenarios, we disaggregate the factors causing accessibility change. Equations describing these decompositions are given in *SI Appendix, Accessibility Change and Determinants*.

The results from the decomposition analysis inform our assessment of sustainability impacts of accessibility changes. We construct two indexes—an emissions index and an equity index—to characterize how accessibility changes have impacted two primary dimensions of sustainability. For the emissions index, we estimate the positive change: Accessibility increases due to residences and employment moving in closer proximity ( $P_{prox_{car, average}}$ ). We subtract the neutral/negative change: Accessibility increases resulting from the increased use of high-speed infrastructure to connect residents and employment ( $P_{speed_{car, average}}$ ):

$$I_{emissions} = P_{prox_{car, average}} - P_{speed_{car, average}} \quad [1]$$

For the equity index, we measure how accessibility has changed for low-income residents relative to the average urban resident. Have accessibility changes benefited average urban residents or residents below the poverty line (low-income) more? The equity index measures the disparity between low-income and average proximity (positive for equity gains) minus speed effects (negative/neutral for equity):



**Fig. 1.** Conceptual framework for how changes in JAC influence social and equity outcomes. Determinants of changes in JAC from 2002 levels are depicted in the “how” column. The combination of determinants and demographics of who is affected can lead to different social and environmental impacts.

$$I_{equity} = P_{prox_{car,LI}} - P_{speed_{car,LI}} - (P_{prox_{car,avg}} - P_{speed_{car,avg}}) \quad [2]$$

We examine how these indexes vary across urban areas and what the results mean for the environmental and social sustainability of urban accessibility trends.

## Results

### Emissions: Accessibility Trends for the Average Resident.

**Accessibility by car.** In the past decade, job accessibility by car (JAC) has increased across the majority of urban areas in the United States. Our analysis shows the median urban increase in JAC was 11% over 2002 levels. Regionally, the greatest change occurred in the Northwest, in medium-sized southern cities, and in large cities in Texas (e.g., Houston and Dallas), where employment numbers have increased in the past decade (Table 1).

The few urban areas that experienced losses in JAC were regionally clustered in areas marked by economic downturns at the end of the US economic recession in 2009. These included metros in the industrial heartland (e.g., Milwaukee; Detroit; and Rochester, NY) and others with increasing unemployment (e.g., Memphis, TN; Los Angeles; and Fresno, CA) (31).

The estimates of accessibility change in Table 1 primarily reflect job growth and loss, which are not the focus of our study. To understand the role that factors like land use configuration and transportation infrastructure have played in shaping accessibility, we decompose JAC changes into individual contributing factors: job growth or loss, changes in the speed of travel, and changes in the proximity between jobs and workplaces (Fig 2A).

Results from the decomposition confirm that job growth has been the dominant driver of JAC increases, accounting for 68% of the total JAC change across urban areas. Land use changes were secondary, with proximity accounting for 24% and speed for 8% of JAC change. However, national averages of speed and proximity effects on JAC do not capture the heterogeneity in factors causing JAC changes across US urban areas or their resulting emissions impacts, so we divide urban areas into four main types:

- i) Rim type ( $\Delta JAC_{speed} < 0$ ,  $\Delta JAC_{proximity} < 0$ , 398 urban areas): Speed and proximity effects have decreased JAC [e.g., cities in Texas (San Antonio, Dallas, Houston, Austin) and Phoenix, Las Vegas, Denver, and New Orleans in Fig. 2A]. Rim types are characterized by single-zone develop-

ment, urban expansion, and employment suburbanization. In the case of New Orleans the results indicate a stark change in employment distribution—a proportionally large loss of residents and jobs in the central area of the city along the coast after Hurricane Katrina.

- ii) Spoke type ( $\Delta JAC_{speed} > 0$ ,  $\Delta JAC_{proximity} < 0$ , 177 urban areas): Speed effects increase and proximity effects decrease JAC (e.g., Philadelphia; Richmond, VA; Milwaukee; and Trenton, NJ in Fig. 2A). This type is characterized by the development of residential or employment centers along highway corridors—often in the form of strip malls and office parks.
- iii) Hub type ( $\Delta JAC_{speed} < 0$ ,  $\Delta JAC_{proximity} > 0$ , 78 urban areas): Speed effects decrease JAC and proximity effects increase JAC (e.g., St. Louis; Washington, DC; San Francisco; and Nashville, TN in Fig. 2A). This type is caused by the redevelopment of neighborhoods near the city center, while exurbs decrease in population. It can also be characterized by transit-oriented development, downtown revitalization efforts, and mixed-use development inside the urban core or near employment centers.
- iv) Sprocket type ( $\Delta JAC_{speed} > 0$ ,  $\Delta JAC_{proximity} > 0$ , 256 urban areas): Speed and proximity effects have further increased the gains made in JAC caused by job growth (e.g., San Jose, CA; New York; Charlotte, NC; and Seattle in Fig. 2A). This type is characterized by a mix of the spoke and hub types. The urban development pattern is dictated by whether speed or proximity effects are dominant. For example, in Seattle, JAC increases are primarily driven by proximity effects characterized by “hub”-like development patterns, whereas increases in Charlotte are mostly driven by speed effects, with “spoke”-like development.

Given that we have defined  $I_{emissions}$  as a difference between proximity and speed effects, these four development types imply different emissions impacts. For the rim and spoke types—where proximity effects are negative—emissions will likely increase. For hub urban areas, proximity effects are greater than speed effects, so emissions will likely decrease. Sprocket development can sometimes be an emissions win and sometimes be an emissions loss, depending on whether speed effects or proximity effects are larger.

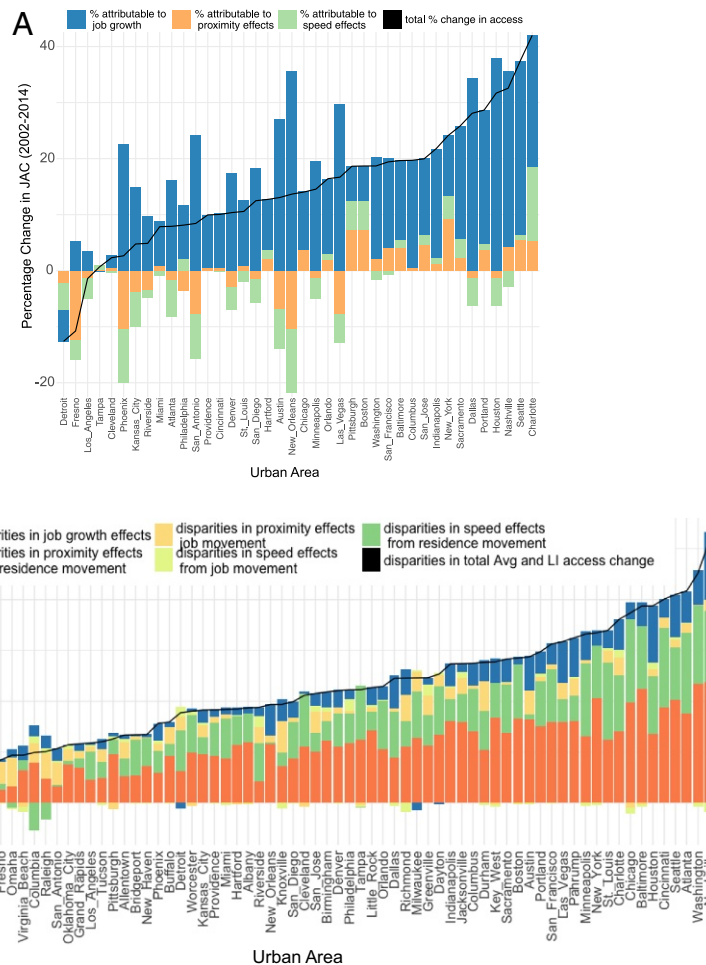
Regionally, we find that most large urban areas in the Northeast have seen a resurgence of urban cores as both residential and employment centers (hub type), increasing the proximity between jobs and residents (Fig. 3), and indicating an emissions win. In contrast, many of the large urban areas in Texas, the West, and the Southwest have continued to see declining proximities between jobs and residences (rim type). Development in the Southeast has been mixed, with mega-urban areas (e.g., Atlanta) declining in speed and proximity effects (rim type), while the majority of the midsized southern cities increased in both speed and proximity effects (sprocket type). The large variability in the processes underlying accessibility dynamics across cities reflects different regional development practices and land values, leading to different emissions impacts.

**Accessibility by transit.** Access to jobs by transit also increased in most urban areas (in 80% of those with bus systems and in all with subway systems). The average resident more than doubled job accessibility by subway (JAS) and gained a 30% increase in job accessibility by bus (JAB). Increases in JAB were especially high in the mid-Atlantic and Southeast, while JAS increased most in Chicago, the Northeast, and the mid-Atlantic (Table 2). These trends add to the JAC results, increasing the likelihood that mega-urban areas of the Northeast and Pacific Northwest and large areas in the Southeast have experienced emissions reductions from their accessibility increases.

**Table 1. Median percentage of change in JAC by region and population size**

| Region and population    | Average | Low income |
|--------------------------|---------|------------|
| <b>Region</b>            |         |            |
| Pacific Northwest        | 20.8    | 18.4       |
| Southwest                | 11.2    | 3.4        |
| West                     | 12.2    | 14.6       |
| Midwest                  | 9.8     | 0.7        |
| Northeast                | 5.4*    | 0.4*       |
| Southeast                | 9.7     | 7.7        |
| Mid-Atlantic             | 19.7    | 12.5       |
| Texas                    | 17.7    | 10.6       |
| Florida                  | 12.0    | 5.4        |
| <b>Population</b>        |         |            |
| Small, <100,000          | 9.7     | 8.4        |
| Medium, 100,000–500,000  | 15.5    | 12.3       |
| Large, 500,000–1 million | 12.5    | 5.4        |
| Mega, >1 million         | 13.9    | 1.7        |

\*Massachusetts employment data available only for 2011–2014.



**Fig. 2.** Decomposition of US accessibility trends. (A) Compositional components underlying trends in JAC from 2002 to 2014. (B) Compositional components causing the disparities in trends in JAC between average and low-income populations. Boston JAC, JAB, and JAS are based on employment from 2011 to 2014.

**Equity: Accessibility Trends for the Low-Income Resident.**

**Accessibility by car.** JAC has also increased for low-income populations (7.7%) but has consistently lagged behind the general population, especially in the largest urban areas (Table 1 and Fig. 4A). Median JAC for urban areas over 1 million people increased by 13.9% and by only 1.7% for low-income residents. This is in contrast with medium and small urban areas, which had far less disparity (average, 15.5%; low income, 12.3% and average, 9.7%; low income, 8.4%, respectively). In some large cities, such as in Washington, DC and Atlanta, there is a 20% difference between JAC increases for the general population and those for low-income residents.

Disparities increase with city size, in part, because as urban areas grow in population, they often grow in both densities of economic opportunities and urban extent. Larger urban areas have pockets of high accessibility where employment opportunities have clustered in the urban core. They also have areas of extremely low accessibility where long commutes are required, usually at the urban outskirts. Together, these elements create greater within-urban variation in accessibility levels, opening up the potential for larger disparities to form. In contrast, small urban areas have less disparity in access because of both their lower job numbers and smaller land areas.

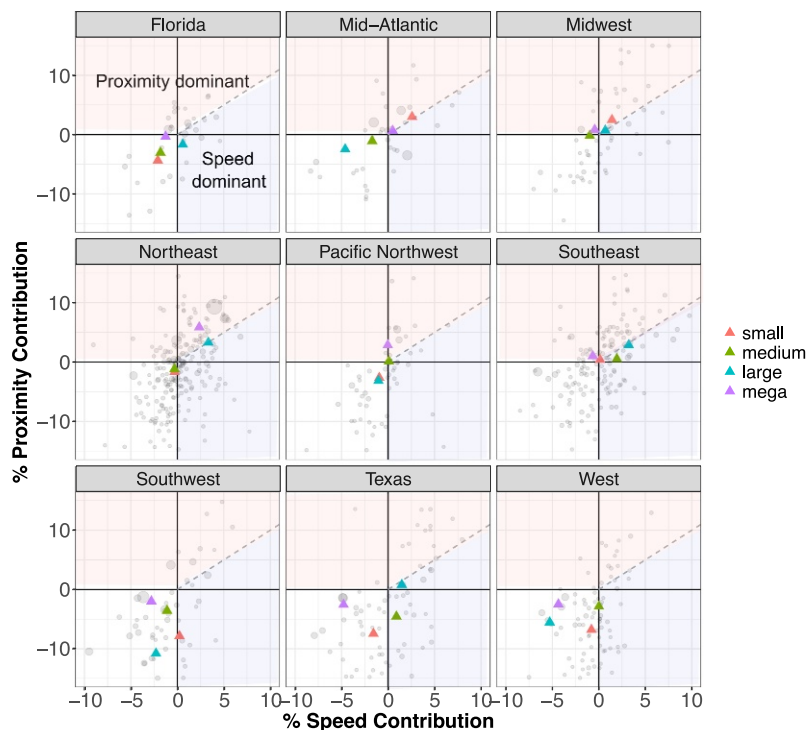
Until recently, accessibility trend studies have been primarily concerned with the decentralization of jobs to the exurbs (32–34). However, we find that the most significant driver of

disparities in accessibility change rates is residential movement, not job movement (Fig. 2B). On average, residential movement accounts for 79% of JAC disparities, whereas job movement accounts for only 9%.

Furthermore, proximity effects from residential movement alone account for approximately half of the disparity between low-income and average accessibility change rates. The dispersal of low-income residents to less accessible neighborhoods and the centralization of wealthier residents within an urban area are observable across US cities, regardless of region.

Given that  $I_{equity}$  is a measure of disparity between average and low-income JAC increases, it is clear from Fig. 2B that most of the larger US urban areas have experienced equity losses. Furthermore,  $I_{equity}$  predicts that urban areas with higher proximity-effect disparities, as opposed to speed-effect disparities, are likely to have more negative equity impacts (e.g., New Orleans vs. Riverside, CA). In these urban areas, low-income residents increasingly must travel longer distances, not just at slower speeds, requiring access to expensive private transport options to reach employment opportunities.

**Accessibility by transit.** Low-income workers experienced decreased JAS (−11.8%) and JAB (−12.3%) over the past decade, a directionally different trend than for average residents. These trends resulted in larger disparities between average and low-income residents using transit (JAS disparity = 116%, JAB disparity = 46%) than for JAC (3%) (Table 2). Disparities in



**Fig. 3.** Types of JAC change in US urban areas. Quadrants denote types *i* (rim) through *iv* (sprocket), depending on the contribution of speed and proximity to accessibility changes. Urban areas in the red region have development patterns that are dominated by proximity effects, whereas urban areas in the blue region have development patterns dominated by speed effects. Population-weighted averages for each region and each urban size group are shown in the solid squares. Some data points in the Northeast plot are affected by curtailed Massachusetts Employment data time series.

JAS were greater than those in JAB, in part, because the subway sample was composed solely of mega-urban areas, where disparities are greatest. However, for urban areas with both transit systems, most had larger disparities in JAS than in JAB (Fig. 4B). On average, urban areas that had both transit types had a 116% disparity in JAS change vs. a 90% disparity in JAB change.

**Emissions and Equity Tradeoffs.** Since most US urban areas have no subway system, and many smaller cities have no bus system, we limit the discussion on emissions and equity tradeoffs to JAC, to include the largest possible set of cities.

The emissions index ( $I_{emissions}$ ) and equity index ( $I_{equity}$ ) are measured for each urban area. Positive values in the  $x$  axis mean that proximity effects (minus speed) have increased more for low-income residents than for average residents. Positive  $y$  values indicate JAC is growing due to increases in proximity, rather than speed (Fig. 5).

By this definition, equity and environmental progress have been practically mutually exclusive. Only 2% of the US population lives in urban areas that have had JAC increases that could reduce both emissions and inequity (quadrant *i*). In contrast, over 50% of the population lives in urban areas where accessibility increases had no inherent emissions reduction or equity value (quadrant *iii*). Accessibility increases that reduced emissions without equity benefits (quadrant *ii*; 219 urban areas) were slightly more common than accessibility increases that reduced inequities without climate benefits (quadrant *iv*; 195 urban areas). However, these emissions “wins” (quadrant *ii*) occurred in larger cities, affecting much more of the US population (43% vs. 9%).

### Discussion

Our analysis suggests change in accessibility is a necessary but insufficient quality to track the processes that impact envi-

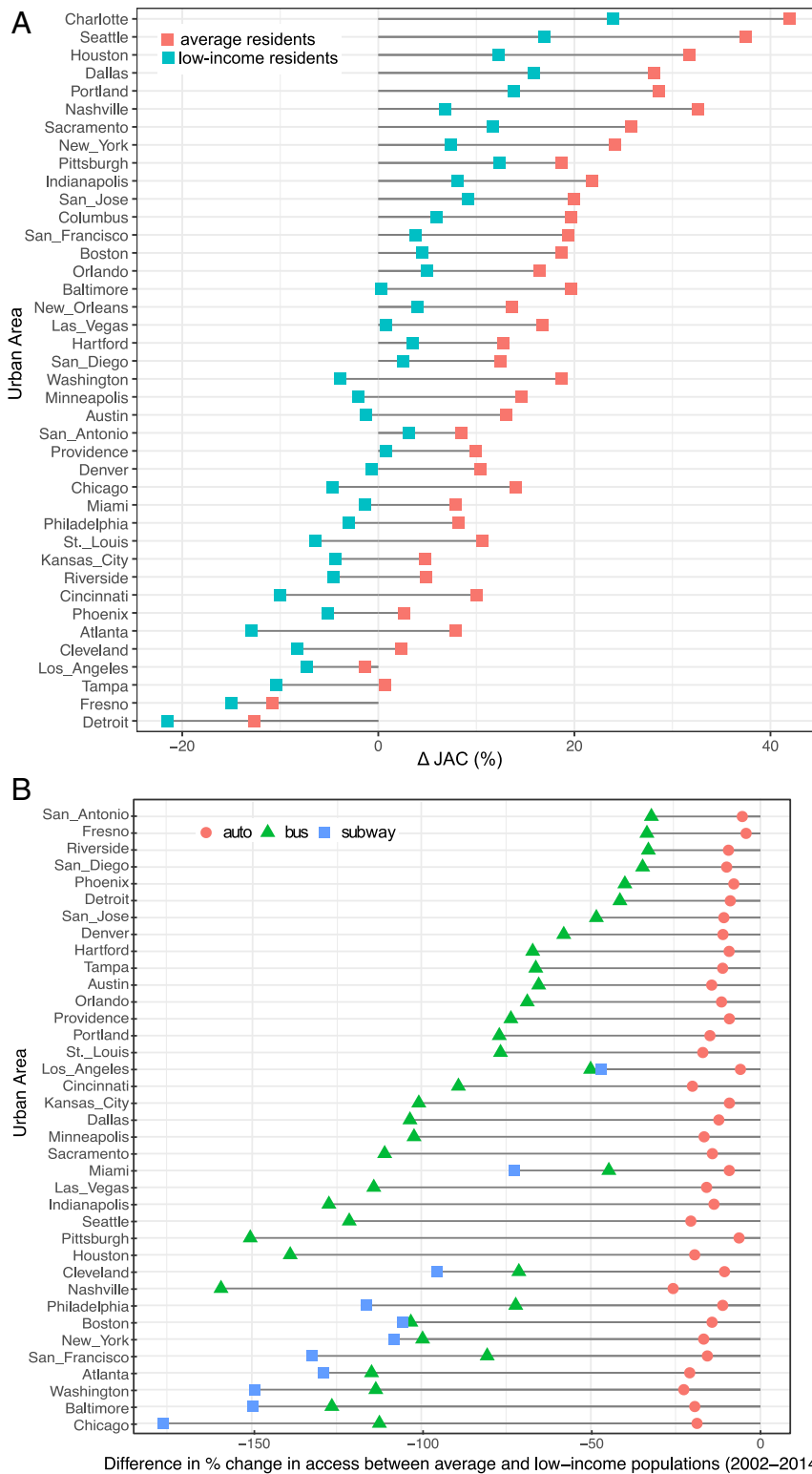
ronmental and social sustainability. If accessibility increases result from greater proximity of jobs and residences, VMT and subsequently emissions can be lessened. However, accessibility increases resulting from increased high-speed travel or job growth will likely have a minimal effect on emissions. Similarly, accessibility increases can sometimes benefit low-income residents and at other times exacerbate existing inequities.

As such, to understand the links between accessibility and sustainability, greater attention must be given to the processes contributing to accessibility trends, instead of solely to the direction and magnitude of the trends themselves. Our analysis shows that although most urban areas (74%) have increased in accessibility, few have achieved accessibility increases in the ways most likely to reduce inequity or emissions, much less both simultaneously. Accessibility to jobs increased across modes (car,

**Table 2.** Median percentage of change in JAB and JAS by region and population size

| Region            | Bus |         |            | Subway |         |            |
|-------------------|-----|---------|------------|--------|---------|------------|
|                   | No. | Average | Low income | No.    | Average | Low income |
| Pacific Northwest | 29  | 19.1    | -6.2       | 0      | NA      | NA         |
| Southwest         | 32  | 23.7    | -12.1      | 2      | 92.1    | 2.6        |
| West              | 16  | 39.7    | -23.5      | 0      | NA      | NA         |
| Midwest           | 35  | 21.6    | -12.3      | 1      | 155.2   | -20.8      |
| Northeast         | 64* | 21.4    | -12.9      | 4*     | 113.2   | -2.9       |
| Southeast         | 12  | 54.7    | -15.7      | 1      | 67.0    | -61.7      |
| Mid-Atlantic      | 13  | 84.3    | -12.6      | 3      | 123.3   | -23.6      |
| Texas             | 14  | 29.0    | -9.2       | 0      | NA      | NA         |
| Florida           | 12  | 33.3    | -18.1      | 1      | 69.78   | -2.7       |

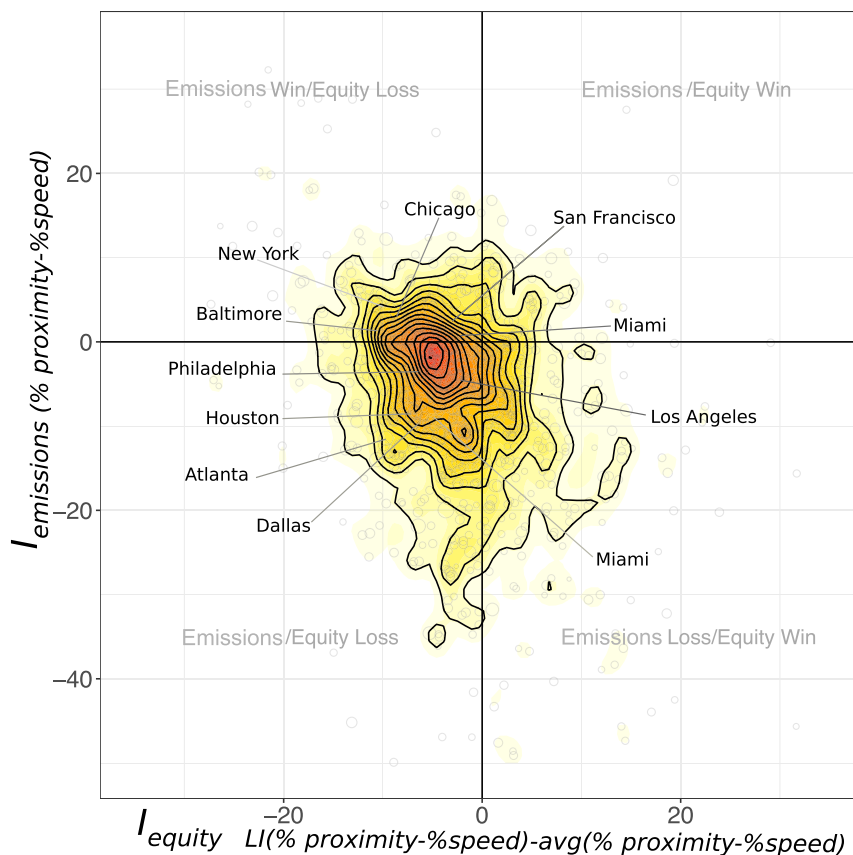
\*Massachusetts employment data are available only for 2011–2014.



**Fig. 4.** (A) Percentage of changes in JAC for average and low-income populations in large urban areas of the United States. (B) Disparities in percentage of change in access between average and low-income populations (average–LI) for different modes of transportation: JAC (circle), JAS (square), and JAB (triangle). Boston JAC is based on employment from 2011 to 2014.

11%; bus, 30%; subway, 113%)—a seemingly positive change from the last half-century of expansive development (35, 36) and suburbanization (37). However, 68% of this change was due to job growth, which does not have a direct impact on the environmental or equity aspects of commuting.

Here, we are interested in accessibility increases that are attributable to land use changes because the associated sustainability impacts are long lasting; locked in by infrastructure, building investments, and zoning policies; and less sensitive to the ebbs and flows of the economy. Therefore, speed and proximity



**Fig. 5.** Equity and emissions indexes describing outcomes of urban accessibility change in four quadrants: emissions and equity win–win (quadrant *i*), emissions win and equity loss (quadrant *ii*), emissions loss and equity loss (quadrant *iii*), and emissions loss and equity win (quadrant *iv*). All 909 US urban areas are plotted as light gray circles, with circle size indicating the urban population size. A kernel density plot is superimposed over the scatterplot, with colors and contour lines illustrating the distribution of the US urban population within the four quadrants.

effects matter for the durability of accessibility trends. Of the remaining 32% of JAC change that was caused by land use and infrastructure configurations, 8% was attributable to speed effects, which have a negligible or negative effect on emissions. Only one-quarter of the JAC change measured across cities was attributable to increased proximity between jobs and housing—the kind of change that is most linked to emissions reductions.

These proximity gains occurred in large urban areas in the East, which had high population growth for younger demographics in the last decade. The majority of northeastern cities started with more compact, mixed-use urban forms, which perhaps created a path dependency in development practices that continued to prioritize proximity over speed during the last decade. Many mid-sized cities have also increased accessibility through proximity effects, by redeveloping their urban cores. Greenville, SC, for example, has undergone a major revitalization of the central business district in the last decade—investing in large public projects that spurred on private investment in mixed-use developments and downtown residential growth (38). Likewise, Pittsburgh has revitalized many of its brown-field properties in the past 10 y, redeveloping the urban riverfronts and bringing in new dense residential development to the city center. Accessibility gains in these urban areas are associated with lower emissions, since increased proximity between employment centers and housing is accompanied by shorter driving distances and more potential for transit and nonmotorized transport.

Our analysis also shows that accessibility increases have not been advantageous for social outcomes in most cities. JAC

changes for low-income populations have consistently lagged behind those for the general population, especially in larger urban areas. Disparities were primarily caused by residential movement; wealthier populations moved closer to jobs in the downtown areas, while low-income residents moved farther from job centers for more affordable housing. This trend runs contrary to conventional theories about the spatial-mismatch hypothesis (39), which focused on the suburbanization of jobs instead of the dispersion of low-income workers. However, job movements accounted for only 9% of the disparities in change rates between the populations—compared with 79% for residential movements.

Low-income population dispersal has negative impacts on residents, above and beyond those caused by the suburbanization of jobs. In both, commute distances are increased, which can decrease commute affordability. Low-income populations spend a disproportionate amount of their income on transportation, a financial burden which is exasperated by both job and housing decentralization. Also in both, policies that aim to reduce travel demand—like toll booths and gas taxes—become increasingly regressive for low-income residents since they must travel farther to work.

However, there are additional difficulties imposed on low-income populations when they are commuting into urban centers for work, instead of living in them. For one, lower-density development makes public transit and carpooling less viable commuting modes. Our results show a decrease of 12% in bus access and subway access for low-income workers, which can complicate commuting for those with less access to private vehicles. Public transit is used more than twice as often

by low-income residents than by the general public (29). Second, loss of proximity of these populations to transit service areas may also reduce the economic feasibility of transit systems themselves, since servicing a more dispersed population is much more expensive. Third, with suburbanization, low-income populations become separated from a myriad of other services that support working families, such as healthcare or food assistance programs (40), that generally accompany the density of city centers. Poverty decentralization may also have benefits for low-income residents (e.g., safety, quality of school systems, breaking up concentrations of poverty), but these benefits are not related to job access and are out of the scope of this paper.

We find that only a handful of urban areas have had JAC increases in the past decade that could provide both environmental and social value simultaneously. Most of these are small cities, with an average population of 160,000. These urban areas are situated in agricultural regions, disconnected from larger urban centers that would impact land prices and draw bedroom community commuters. Part of the reason these regions have more equitable accessibility dynamics is that the housing prices inside their urban cores are comparable to, or below, average housing prices for the larger metropolitan area (41), indicating that demand for city core living is low. Thus, although there may be increased investment in the central urban areas, low-income populations have not been displaced.

Although transit accessibility increases (JAS and JAB) are excluded from the final portion of the analysis, emissions and equity impacts from JAS and JAB are another, perhaps even starker example of emissions and equity tradeoffs. Our results show that access to jobs by transit increased almost ubiquitously across all applicable urban areas in our sample, often doubling. However, for low-income residents, both bus and subway access decreased.

The results of this study point to a key sustainability tradeoff between accessibility that mitigates emissions and accessibility that promotes the welfare of low-income residents. It indicates that, at least in the last decade, no optimal solution that satisfies both facets of sustainability has been reached. Potentially a Pareto optimal cannot be reached given that accessibility is a commodity and thus an input in the market value of land. Without intervening pro-equity strategies, revitalization efforts that increase accessibility for the general public could leave low-income residents behind.

Instead, a critical question for future research may be, Where does it make sense to invest in accessibility improvements tailored specifically for low-income residents, and where would accessibility improvements efficiently lessen emissions? Following recent theoretical arguments in sustainability science (42), accessibility improvements will affect human and environmental wellbeing differently at different scales. Mobility-limiting strategies (e.g., tolls, gas taxes, and parking pricing) may reduce emissions at the urban scale, but may also be increasingly burdensome to low-income individuals in cities where walkable, mixed-use, highly accessible neighborhoods are not affordable. Urban areas that propose mobility-enhancing strategies (e.g., certain types of fixed guideway transit expansion) to connect workers to the labor market may risk increasing residential land values along transit lines (43–47) and unintentionally evict low-income residents. More research is needed on how publicly and privately funded climate mitigation efforts that increase accessibility affect housing markets and municipal goals for social equity. The consideration of these tradeoffs between different dimensions of sustainability at different scales will be critical to drafting pro-equity, pro-environmental land use and transportation policy.

There are several limitations to the methodology used in this study that may influence the results. While our gravity-based

accessibility measure overcomes many of the shortcomings of contour measures of accessibility, it does not consider how well job locations match the skills of residents, which could significantly change the accessibility results, given the skill sets of low-income workers can be different from those of the average population. It also does not take into account the affordability of transport modes or traffic, which can enable or restrict access to economic opportunities.

Traffic has a large effect on peak hour commuting in some urban areas and a minimal effect in others, which limits the comparability of accessibility levels between different cities. Here, the effect of traffic is moderately controlled for, given that we are looking at change in accessibility over time. However, given that many urban areas in the United States have grown in population between 2002 and 2014, congestion has also likely increased. These congestion increases are not captured, which could mean our estimates of JAC increases, for both average and low-income residents (shown in Fig. 4), may be artificially high.

Congestion also changes the distribution of accessibility within an urban area, for peak commuting hours. If congestion has primarily increased on highways over the past decade, low-income JAC may have been disproportionately affected, because of the suburbanization of poverty (shifting the results toward greater equity losses). In urban areas where JAC gains were speed dominated, these gains would be minimized. Alternatively, if traffic has primarily increased on the local streets of central business districts, JAC change for low-income and average residents may be more equal than we have estimated. However, JAC increases would be more dependent on speed, providing fewer emissions and equity benefits. Increased congestion makes it even more important to have workplaces near residences, so multimodal travel, like walking, biking, and transit, can help offset increased commuting loads.

In addition to these limitations, this study assumes that accessibility plays a large role in actual commuting behavior. However, commuting behavior is shaped by many factors that have not been included—e.g., locational compromises between two-income households and social networks. Individual and utility-based metrics that track actual residential and employment matches can take these concerns into account (25), but are difficult to apply across large numbers of cities because of their data intensity. While our study points to regional trends in sustainability tradeoffs, inclusion of these other aspects would be critical to answer questions at the urban level about where accessibility changes benefiting emissions or equity should be prioritized.

## Materials and Methods

Fine-resolution datasets on urban road and transit infrastructure (US census Tigerlines, OpenStreetMap) (20, 21), employment data (LEHD-LODES) (23), poverty population data (US Census Summary File 3) (48), road classifications (US Census Tigerlines (20), and household location data (US Census) (20, 22) were collected as inputs to the accessibility computation. Each of these datasets is transformed into a consistent  $1 \times 1$ -km grid.

Accessibility to jobs is calculated for bus, subway, and car travel in all US metropolitan and micropolitan areas in the contiguous US for years 2002 and 2014, using a gravity-based measure (19). Travel time cost is estimated using free-flow estimates of driving, subway, bus, and walking speed, depending on road class and infrastructure type. We use a negative exponential impedance function which has been shown to be closely tied to travel behavior (49) and a constant  $\beta$  to allow comparability across urban areas. For each residential grid cell (origins), we calculate the cumulative accessibility to every other grid cell in the entire urban area (destinations), weighted by the number of jobs in the grid cell and inversely by the time cost to reach it. Accessibility levels and accessibility change for an urban area are calculated as a population-weighted mean/difference, where the population grid is either all residents (average) or residents below the poverty line (low income).



We disaggregate accessibility change into its individual determinants using a counterfactual decomposition, isolating the effect of job location shifts, population location shifts, and job growth/loss on JAC change. Proximity and speed effects are isolated by creating a counterfactual where all road speeds are 30 mph. From these determinants, we create an environmental index and an equity index for each urban area. The environmental index is calculated by the percentage of accessibility change contributed from proximity effects minus that from speed effects. The equity index is equal to the disparity between low-income and average populations for JAC change from proximity effects minus change from

speed effects. Details on these datasets and methods are provided in *SI Appendix*.

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