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Dividing Highways: Barrier Effects and Environmental Justice in California

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RESEARCH REPORT

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Dividing Highways: Barrier Effects and Environmental Justice in California

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16. Abstract
We examine the barrier effects of freeways in California. We analyze the association between freeways and three measures of nearby street connectivity: the composite Street Network Disconnectedness index (SNDi), circuity, and the distance between crossings – underpasses or bridges that enable people to cross the freeway. We also assess the quality of a sample of these crossings for pedestrians and cyclists. We find that barrier effects are most pronounced in communities of color. We also find that even where crossings exist, they are unpleasant or even hazardous for pedestrians and cyclists because of high-speed traffic on on- and off-ramps, and because large volumes of traffic are funneled through a small number of crossings rather than being distributed over a wider network.

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About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

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The UCLA Institute of Transportation Studies and UCLA Center for Neighborhood Knowledge acknowledge theGabrielino/Tongva peoples as the traditional land caretakers of Tovaangar (the Los Angeles basin and So. Channel Islands) and that their displacement has enabled the flourishing of UCLA. As a land grant institution, we pay our respects to the Honuukvetam (Ancestors), ‘Ahiihirom (Elders) and ‘Eyoohiinkem (our relatives/relations) past, present and emerging.

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Executive Summary

Executive Summary

Limited-access freeways physically divide urban neighborhoods, creating “severance” or “barrier effects” as streets that would otherwise be continuous dead-end at a freeway. Unless the freeway is elevated or in a tunnel, crossings are limited to purpose-built bridges or underpasses, often forcing a lengthy detour for pedestrians and cyclists. Even at these crossings, physical severance can be exacerbated by poor or missing sidewalks, lighting, or bicycle lanes; fast-moving traffic entering or exiting the freeway; and in the case of pedestrian bridges over the freeway, steps or circuitous ramps.

In this report, we quantify the impact of freeways on severance in California, with a particular focus on Los Angeles County. We analyze the association between freeways and the connectivity of local street networks, and how freeways affect pedestrian and bicycle access to rail stations and other major transit stops. We analyze the distance between crossings – underpasses or bridges that enable people to cross the freeway. For a sample of crossings in Los Angeles County, we audit their quality for pedestrians and cyclists.

We also examine whether severance creates or perpetuates environmental injustices. There is a wealth of historical evidence that documents how freeway routing decisions in the United States were motivated by racial prejudice, and how the air and noise pollution impacts of freeways disproportionately fall on communities of color. In this report, we analyze whether similar injustices also occur through severance – for example, whether connectivity, crossing distances, and crossing quality at freeways vary with the racial demographics of a neighborhood.

While the severance impacts of freeways have been studied extensively in specific neighborhoods, ours is the largest-scale study to date, and our methods can be replicated at scale outside of California. Our study is also one of the few to examine the relationship between severance and environmental justice.

Our key findings are as follows:

1. Freeways reduce connectivity in many places, particularly where they run through previously established urban areas. However, the effects are surprisingly heterogeneous, and hard to isolate because freeways are often built though the parts of cities with the most connected streets – for example, on flatter ground. To isolate causal effects, future analysis would ideally digitize the historical street network prior to freeway construction, in order to enable a before-after comparison of connectivity.

2. Severance is most pronounced in communities of color. We do not isolate any specific causal mechanism or the role of deliberate racial bias. However, environmental injustices are fundamentally about disparate impacts regardless of whether those are brought about by intentionally discriminatory practices, and those disparities certainly exist in the case of severance.

3. Quantitative connectivity metrics such as circuity underestimate the severance impacts of freeways. Freeway crossings are normally unpleasant or even hazardous for pedestrians and cyclists because of infrastructure design and because large volumes of traffic are funneled through a small number of crossings rather than being distributed over a wider network. These crossings are typically built with freeway access as the main consideration, not safety and connectivity for pedestrians and cyclists. Moreover, the sparsity of crossings means that there is little reasonable alternative in some neighborhoods; removing the "poor" crossings more than doubles circuity in our analysis.

What do our findings imply for planning and policy? For newly constructed freeways, severance can be reduced by maintaining the continuity of at least some local street connections, especially where no on- or off-ramp is provided. When crossings would otherwise be few, each additional crossing may have a large effect on connectivity. For existing freeways, building new crossings (e.g., pedestrian or bicycle bridges) can be valuable, although it can be challenging to design them in a way that provides direct routes and real and perceived safety. But the poor quality of many existing crossings points the way to a lower-cost, more quickly implemented approach: widening sidewalks, adding a buffer between pedestrians and moving traffic, and providing signals or shorter turn radii to slow traffic exiting or entering a freeway. Our analysis indicates a data-driven way to prioritize such improvements, that can take into account environmental justice and access to transit as well as overall street connectivity.

Efforts to address severance, however, should not neglect consideration of the – more important – impacts of freeways on air and noise pollution, which are also concentrated in communities of color. Rather than addressing the negative consequences of freeways in a piecemeal fashion through (say) pedestrian bridges, sound barriers, and supplying air filters to nearby households, planners and policy makers might look to cities such as Boston and Oslo that are undergrounding road infrastructure, or to Seoul and San Francisco that have started to remove some freeways altogether.

Contents

Introduction

Limited-access freeways (highways or motorways[1]) have far-reaching environmental and social consequences. At the regional scale, they induce travel by private car (Duranton and Turner 2011) and exacerbate urban sprawl (Baum-Snow 2007; Garcia-López 2019). At the local scale, they contribute to air and noise pollution, habitat destruction, and physically divide urban neighborhoods. The latter effect is typically referred to as "severance" or "barrier effects": streets that would otherwise be continuous might dead-end at a freeway, forcing a lengthy detour for pedestrians and cyclists (Figure 1).

The negative consequences of freeways often fall disproportionately on people of color. In part, these environmental injustices result from broader inequities in the housing and labor markets, meaning that people of color are less likely to be able to afford housing further from the freeway. But they also result from racist practices that targeted particular neighborhoods for freeway construction (Rothstein 2018).

In this report, we quantify the impact of freeways on severance in California, with a particular focus on Los Angeles County. We analyze the association between freeways and the connectivity of local street networks, and how freeways affect pedestrian and bicycle access to rail stations and other major transit stops. We analyze the distance between crossings – underpasses or bridges that enable people to cross the freeway – and assess their quality for pedestrians and cyclists. And we examine how severance creates or perpetuates environmental injustices, through analyzing how connectivity, crossing distances, and crossing quality vary with the racial demographics of a neighborhood.

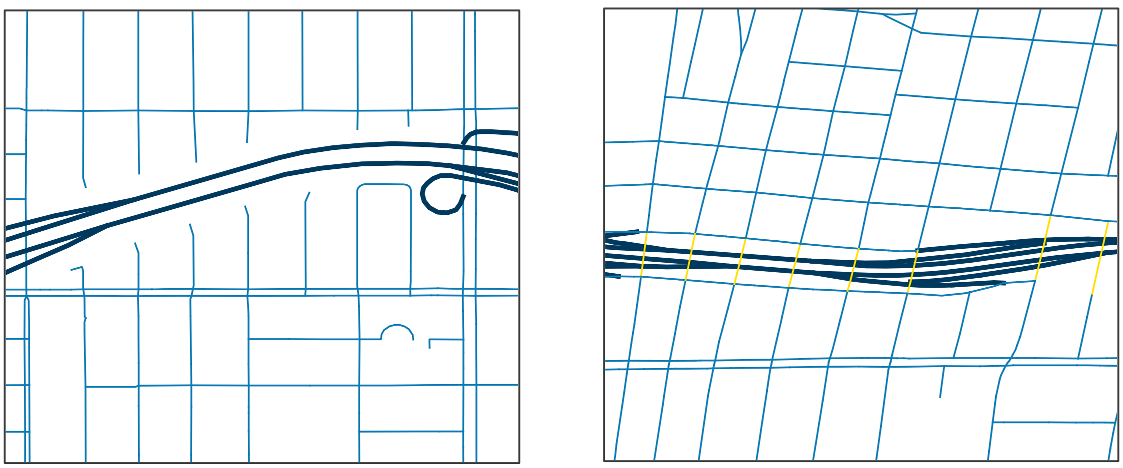


Figure 1: Schematic of severance effects. Freeways (*darker color*) create severance or barrier effects through creating dead-end streets and lengthy detours (*left*), unless the local street network is continued across freeways via over- or underpasses (*right*).

[1] In this report, we consider the term freeways to be synonymous with highways or motorways – in all cases, a limited-access roadway that is normally closed to non-motorized travelers. Our freeway network data come from OpenStreetMap, which defines a motorway as: "A restricted access major divided highway, normally with 2 or more running lanes plus emergency hard shoulder." See https://wiki.openstreetmap.org/wiki/Map_features#Roads.

While the severance impacts of freeways have been studied extensively in specific neighborhoods, ours is the largest-scale study to date, and our methods can be replicated at scale outside of California. Our study is also one of the few to examine the relationship between severance and environmental justice.

We find that severance effects are difficult to identify without access to digitized historical maps, because freeways are often routed through neighborhoods with the most connected streets – for example, because of flat topography. However, we do find that severance is most pronounced in communities of color. We also find that even where crossings exist, they are unpleasant or even hazardous for pedestrians and cyclists because of high-speed traffic on on- and off-ramps, a lack of bicycle lanes, sidewalks and other infrastructure, and because large volumes of traffic are funneled through a small number of crossings rather than being distributed over a wider network. Thus, quantitative connectivity metrics such as circuity underestimate the severance impacts of freeways.

Freeways, severance, and justice

Freeways and severance

Surface roads of all types that carry high traffic volumes impede pedestrian and bicycle travel. This impedance is typically referred to as “severance” or the “barrier effect,” and we use the two terms interchangeably in this report. Physical barriers are the most obvious mechanism through which roads hamper non-motorized travel across them, especially on limited-access freeways. However, even where physical barriers do not exist, high traffic volumes can make it hard to cross a street, and noise and dust impose psychological barriers and represent significant environmental hazards. (For reviews, see Anciaes, Jones, and Mindell 2016; van Eldijk, Gil, and Marcus 2022; Mindell and Anciaes 2020.)

Severance is not inherently a problem. In some instances, there may be no reason for pedestrians or bicyclists to travel to a destination on the other side of the road. For example, communities might have grown up independently on each side of the road after it was built (Handy 2003). Social networks and school catchment boundaries might always have been separated by a roadway, or one side of the roadway might be under agricultural or industrial uses that attract few trips. More commonly, however, severance reduces accessibility to destinations such as stores, parks, and schools, and in some cases it also reduces social capital. One of the earliest studies found that residents of a low-traffic street in San Francisco had three times as many friends and twice as many acquaintances as residents of a comparable high-traffic street (Appleyard, Gerson, and Lintell 1981). Subsequent studies have shown similar effects on social capital (e.g. Bosselmann, Macdonald, and Kronemeyer 1999).

Limited-access freeways, the focus of this report, provide the most tangible manifestation of barrier effects through physically severing the local street network. Unless the freeway is elevated or in a tunnel, crossings are limited to purpose-built bridges or underpasses, whether at interchanges (on- and off-ramps) or on local streets or pedestrian crossings that do not provide access to the freeway. Even at these crossings, physical severance can be exacerbated by poor lighting, non-existent or poorly maintained sidewalks, a lack of bicycle lanes, fast-moving traffic entering or exiting the freeway, and in the case of pedestrian bridges, steps or circuitous ramps.

For these reasons, freeways typically reduce network connectivity and accessibility, and other contributors to walkability and bikeability as well. For example, high-school students in Davis, California are less likely to bicycle if they have to cross the freeway, in part because of the indirectness of the available routes (Emond and Handy 2012). In turn, freeways are likely to reduce non-motorized travel and increase car travel — an effect that comes on top of the induced travel that comes from higher car travel speeds and regional land use changes (Cervero 2002; Duranton and Turner 2011). Freeway-induced severance can affect social exclusion and health outcomes as well, although the latter are hard to separate from the impacts of freeways on noise and air quality. On the other hand, new freeways may encourage walking if they divert traffic away from local streets, and build social capital through increasing accessibility by private car, thus allowing people to maintain connections with more physically distant friends and family (Nimegeer et al. 2018).

Empirical studies of severance are relatively limited, especially in comparison to the much broader literature on the air quality and noise impacts of roads (Anciaes et al. 2016; van Eldijk et al. 2022). In some cases, qualitative analysis examines the impact of new roads on social networks and perceptions of a neighborhood (e.g. Nimegeer et al. 2018). Some studies use connectivity or accessibility measures, quantifying the impacts of a road on circuity or the decrease in accessibility to destinations such as schools and parks (e.g. van Eldijk 2019; Handy 2003). Others seek to assess severance in monetary terms, through estimating residents' willingness to pay to bury a freeway or to avoid a detour to cross a busy street (e.g. Anciaes and Jones 2020; Grisolía, López, and de Dios Ortúzar 2015). Normally, these analyses are small-scale case studies of a new freeway or a project to place part of an existing road in a tunnel (e.g. van Eldijk 2019).

Severance and justice

The racist legacy of freeway building has recently been spotlighted at the highest levels of government. In 2020, the California State Transportation Agency Secretary stated: "[Transportation] improvements historically have disproportionately benefitted certain segments of the population. Far too often, past transportation decisions quite literally put up barriers, divided communities, and amplified racial inequalities, particularly in our Black and Brown neighborhoods" (Kim 2020). More recently, US transportation secretary Pete Buttigieg called out the "racism" inherent in freeway design choices (White House 2021). These comments have been reflected in the popular media as well, with the Los Angeles Times running an opinion piece labeling freeways as "insidious monuments to racism and segregation" (Fleischer 2020).

These statements are grounded in a wealth of historical evidence that documents how freeway routing decisions in the United States were, in part, motivated by racial prejudice. In cities from Santa Monica, California to Richmond, Virginia, routes were chosen because they would raze Black and/or lower-income neighborhoods, as part of a broader strategy of urban renewal and removal of "blight" (Bullard & Johnson 1997; Rothstein 2018; Dottle, Bliss & Robles, 2021; Gordon 2021). In some places, freeway planners appear to have been motivated by the lower costs of right-of-way acquisition in neighborhoods of color, or as in Beverly Hills and the French Quarter of New Orleans, the more effective political opposition by affluent and white residents (Dottle, Bliss & Robles, 2021; Haddad & Morrison 2021), but the end result was the same even in the absence of explicit racial animus.

In other cases, freeways were constructed as barriers between predominantly white and predominantly Black neighborhoods – severance was the feature, not the bug. In Atlanta, for example, I-20 West was designed as a dividing line that would perpetuate existing patterns of segregation, and other highways were intended to prevent black "encroachment" or avoid white flight (Bayor 1988). The city even went so far as to close off sections of road and create dead ends to avoid connections between Black and white neighborhoods (Bayor 1988).

In contemporary environmental justice studies, the air and noise pollution impacts of freeways have received most attention, typically finding that people of color are more likely to live close to a freeway and thus be impacted by its pollution (Chakraborty 2006; Forkenbrock and Schweitzer 1999; McEntee and Ogneva-Himmelberger 2008; Rowangould 2013; Schweitzer and Valenzuela 2004). The negative health outcomes observed include low birth weights, asthma, and hospital admissions for respiratory disease, and in some cases cancer. Such injustices might be expected to emerge over time even if original freeway routing decisions were race neutral. Discrimination in the housing market and wealth inequality leave many people of color with fewer housing options, in contrast to white households who are more likely to have the means to choose less-polluted neighborhoods (Banzhaf, Ma, and Timmins 2019).

There is less evidence, however, regarding the relationship between severance and environmental justice. Even if people of color are more likely to live close to a freeway, that does not automatically translate into disparities in severance, partly because severance impacts might be felt over a wider area, and partly because severance can be mitigated through frequent over- and underpasses for local traffic and/or pedestrians. On the other hand, it is plausible that discretion in the planning process over the provision of pedestrian bridges and local street crossings might exacerbate injustices, for example if wealthy and/or white residents have better success in lobbying for these improvements. For example, in Pasadena, city officials threatened to refuse to sign street closure agreements as part of their efforts to reroute freeways away from wealthier neighborhoods (Ramirez et al. 2022).

Methods

Empirical setting

Our empirical setting is the state of California. California is home to one of the world's earliest freeways, the Arroyo Seco Parkway which opened in 1940 (Haddad and Morrison 2021), and it continues to build and expand freeways in the 21st century. Thus, our dataset spans many eras of freeway design standards, as well as a range of urban forms from streetcar suburbs to car-oriented sprawl. In practical terms, we study a single state because some of our data (specifically freeway opening dates) is California-specific.

For the audit of crossing quality and the analysis of transit access, we focus on Los Angeles County; many of our graphical illustrations are also drawn from the Los Angeles region. Because our sample of crossing quality is limited, we chose to concentrate on a particular geographic area in order to limit variation on other dimensions. Our transit data, meanwhile, is also Los Angeles specific. Note that the county is the most populous in the United States; at more than 10 million, it exceeds most US states and even many countries.

Research approach

We analyze four different measures of severance: (i) the Street Network Disconnectedness index (SNDi), (ii) one of SNDI's component measures, circuity, (iii) the distance along a freeway to the nearest crossing (over- or underpass), and (iv) the quality of crossings. Each of these measures is discussed in more detail below.

We then analyze the association between SNDi and circuity and proximity to a freeway, through comparing areas (grid cells) that are within 400m (about a quarter mile) of a freeway to those that are more distant (400-800m, although we also analyze other distance bands). The 400m and 800m (roughly one-quarter and one-half mile) thresholds equate to typical rules of thumb for walking distances to transit (Guerra, Cervero, and Tischler 2012). We test the hypotheses that freeways reduce street connectivity through barrier effects, and that these effects are more severe in neighborhoods with more people of color.

Our other two measures – distance between crossings and crossing quality – do not lend themselves to a comparison between different freeways' proximity bands, because by definition these measures only exist at a freeway. Instead, we consider the distribution of these measures, and how they vary with racial demographics.

Data sources

Our data sources on the local street and freeway network come from OpenStreetMap (OSM, downloaded September 29, 2021). The opening dates of each freeway segment were provided by the California Department of Transportation (Caltrans), and we matched the Caltrans freeways segments to the OSM network. Data on population counts and race are from the US Census 2020 block-level files, which we aggregate to 1km^2 grid cells to match our SNDi calculations (see below), using an area-weighted interpolation. We also control for topography, since this is an important determinant of street connectivity (Barrington-Leigh and Millard-Ball 2017), using elevation data from the USGS Global Multi-resolution Terrain Elevation Data model (GMTED2010) which we convert to slope using PostGIS.

Measuring Severance

Connectivity

The Street Network Disconnectedness Index (SNDi) is a composite measure of severance. Its components include circuity (the ratio between Euclidean and network distance for nodes within various distance bands, as shown in Figure 2), the proportion of dead ends, and graph-theoretic measures such as the proportion of edges that are network bridges. These components are combined using Principal Component Analysis; SNDi is the first component. Full details of the measures, the calculation and graph simplification methods, and details of validation are provided in Barrington-Leigh and Millard-Ball (2019). We calculate SNDi for each 1km^2 grid cell.

We also analyze one of the components of SNDi: circuity. For each origin node (street intersection), we calculate the Euclidean and network distance to all other nodes within 500m (Figure 2). We then sum these distances for each origin node with a grid cell, and calculate circuity as the log of the ratio of Euclidean to network distance. Note that bicycle and pedestrian paths are considered in this analysis when they provide the shortest route, but their nodes (e.g. the intersection between two pedestrian paths) are not counted as origins. For further details, see Barrington-Leigh and Millard-Ball (2019).

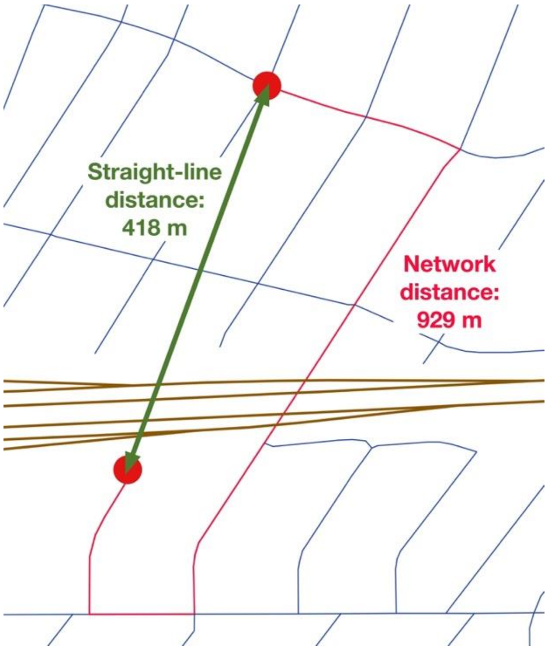


Figure 2: Circuity. For this pair of nodes, separated by the freeway shown in brown), the straight-line distance is 418m, while the distance via the street network is 929m, giving a distance ratio of 2.22. This calculation is repeated for each pair of nodes within the distance band (e.g. 400m).

Distance between crossings

We identify freeway crossings as those edges (i.e., street segments) that intersect with a freeway. We classify each crossing as (i) a freeway entrance or exit (i.e., a ramp or interchange); (ii) an intersecting street that does not give freeway access; or (iii) a bicycle- or pedestrian-only path. The first category is defined as edges that directly give access to freeway ramps.[2] The third category is defined based on attributes tagged in OSM (e.g. bicycle path). Figure 3 shows an example of each type of crossing.

After identifying all crossings, we compute the average distance between crossings for each grid cell. We also compute the average distance for each freeway according to its name (e.g. I-5 or US 101). The Appendix derives and explains the algorithm. Note that this metric (average distance between crossings) is linearly related to the expected distance to the closest crossing for any random point on the freeway, as explained in the Appendix.

[2] Note that we aggregate intersections according to the process in Barrington-Leigh and Millard-Ball (2019); nodes within 10m of each other are considered as part of the same functional intersection.

Figure 3: Examples of crossing types. From left to right, the images show a crossing at a freeway entrance/exit; an intersecting street that does not provide freeway access; and a pedestrian/bicycle-only crossing. The examples are on Highway 110 near Dodger Stadium, Los Angeles. Images: Bing Maps and Google Street View.

Crossing quality

We evaluate the quality of a random sample of 100 crossings in Los Angeles County, analyzing Google Street View imagery. The location of each sampled site is shown in Figure A-1. (See Biljecki & Ito 2021 for a review and discussion of the advantages of street view tools.) We adapt existing audit frameworks for qualitatively evaluating pedestrian and bicycle conditions (Boarnet et al. 2006; Furth, Mekuria & Nixon 2016; Kurka et al. 2016; Steinmeitz-Wood et al. 2019), along with the planning methods in First/Last Mile Plans from the Los Angeles County Metropolitan Transportation Authority (e.g. Lieb et al. 2019), to develop our Freeway Crossing Quality Audit framework (Figure 4). Our framework contains three categories: the pedestrian walkway, crosswalks across any entrance and exit ramps, and bicycle facilities. Within each of these categories, we assess crossing quality based on a series of criteria (speed limit, signage present, shade cover, etc.) as shown in Appendix Table A-1. A score of “4” indicates the highest quality crossings, and “1” denotes the lowest quality. We also calculate a composite score as the average of the scores in the three categories.

	Score 4 (Highest quality)	**Score 1 (Lowest quality)**
Walkway		
Ramp		
Bicycle facilities		

Figure 4: Examples of crossing quality ratings. The specific criteria are provided in Appendix Table A-1. Images: Google Street View.

Results

Freeways and connectivity

We begin by presenting graphical evidence about the relationship between freeways and street connectivity. In general, the presence of a freeway is associated with reduced street connectivity. Figure 5 shows an example from Interstate 10 in West Adams, Los Angeles, where many of the previously continuous streets (lower image) now dead-end into the freeway. SNDi increases from 1.0 in the grid cell just north of the freeway to 1.7 in the grid cell through which the freeway runs. Two of the component measures of SNDi, circuity and the fraction of dead ends, increase as well.

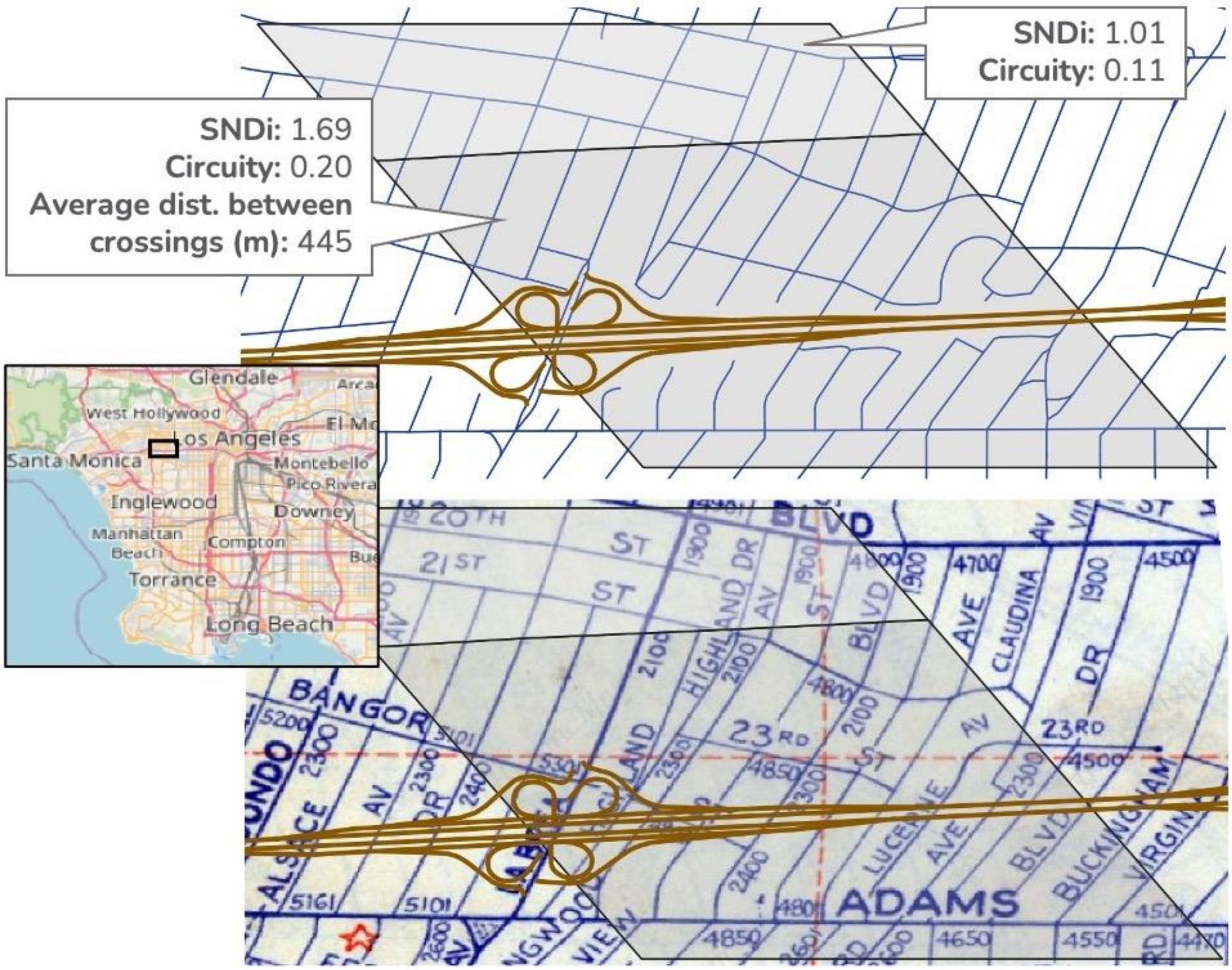


Figure 5: Example of connectivity differences near freeways and the original street network prior to freeway construction. Basemap (top): OpenStreetMap contributors. Historic map (bottom): Thomas Bros. Los Angeles County 1957 Street Atlas via Historic Map Works.

The distributions of two measures of street network connectivity, at different distances from freeways, and for all urban counties in California (upper panels) and for Los Angeles County specifically (lower panels) are shown in Figure 6. Each line gives the frequency distribution for a different distance band. Grid cells within 400m of a freeway (green lines) have less connected streets and more circuitous street networks compared to those 400-800m (orange lines) and 800-1600m (purple lines). At even greater distances from the freeway (1600m or more), there is more variation in SNDi, perhaps indicating the greater heterogeneity of built forms and topography in this larger area.

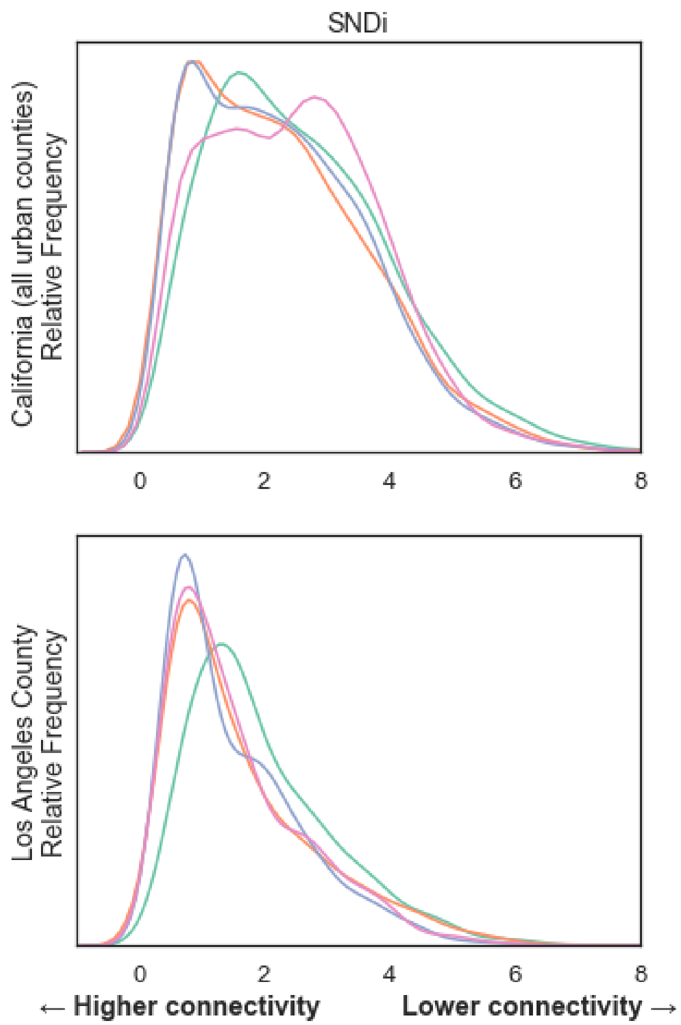


Figure 6: Frequency distributions of street connectivity by distance band. The upper panels show all urban counties in California; the lower panels Los Angeles County only. The left panels show SNDi; the right panels one of its component measures, circuity. Estimates are population weighted.

The relationship between street connectivity and freeways, however, is not straightforward, as can be seen visually in the example of Los Angeles in Figure 7. The left panel shows the strong influence of topography – mountainous areas have lower connectivity as it is harder to avoid dead-ends and dendritic, circuitous networks where slopes are steep. But it also shows the contrast between the older, gridded neighborhoods of south and west Los Angeles, compared to post-WWII suburbs typified by cul-de-sacs. The right panel, however, shows that even the immediate area around freeways can have more or less connected streets than more distant (400-800m) grid cells. In some cases – for example, where a freeway runs through a mountain pass – the freeway-adjacent streets are more connected than those further away (blue cells in Figure 7B). But even where the influence of topography is less dominant, some freeways have a scarcely detectable impact on connectivity (yellow cells) while in others the negative impact is readily apparent (red cells).

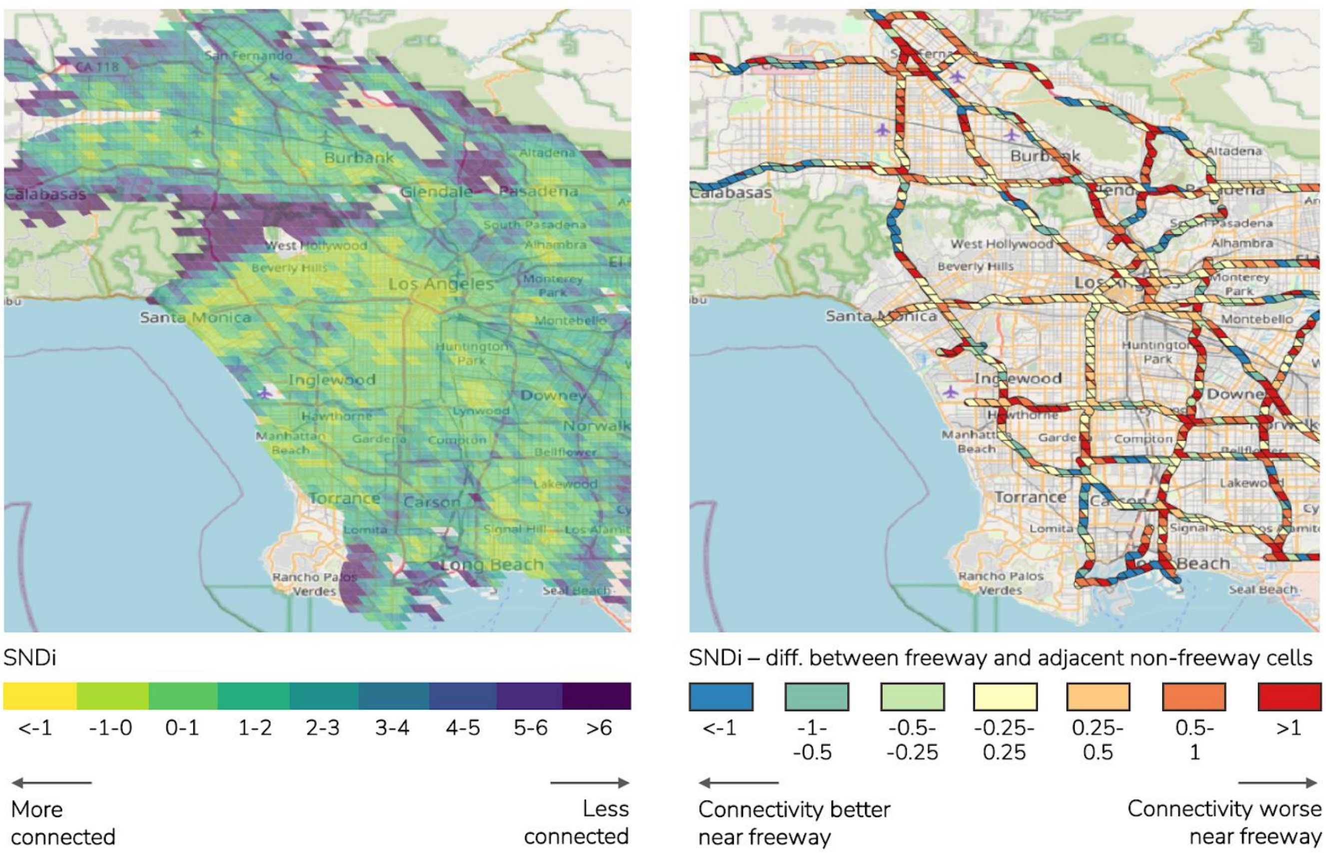


Figure 7: Connectivity patterns in Los Angeles county. The left panel shows the variation in SNDi across the county, with the mountainous areas contrasting with the pre-WWII grids of south and west Los Angeles. The right panel shows the difference in SNDi between areas within 400m of a freeway and adjacent grid cells between 400-800m from a freeway. Freeway cells in orange and red have SNDi values greater than their non-freeway neighbors. Basemap: OpenStreetMap contributors.

Trends over time

One might hypothesize that growing awareness of severance effects over time might mean that more recently constructed freeways were designed to have less impact on street connectivity than those built in earlier periods. However, Figure 8 indicates no such relationship - the relationship between freeways and severance is uniform across freeway opening dates.

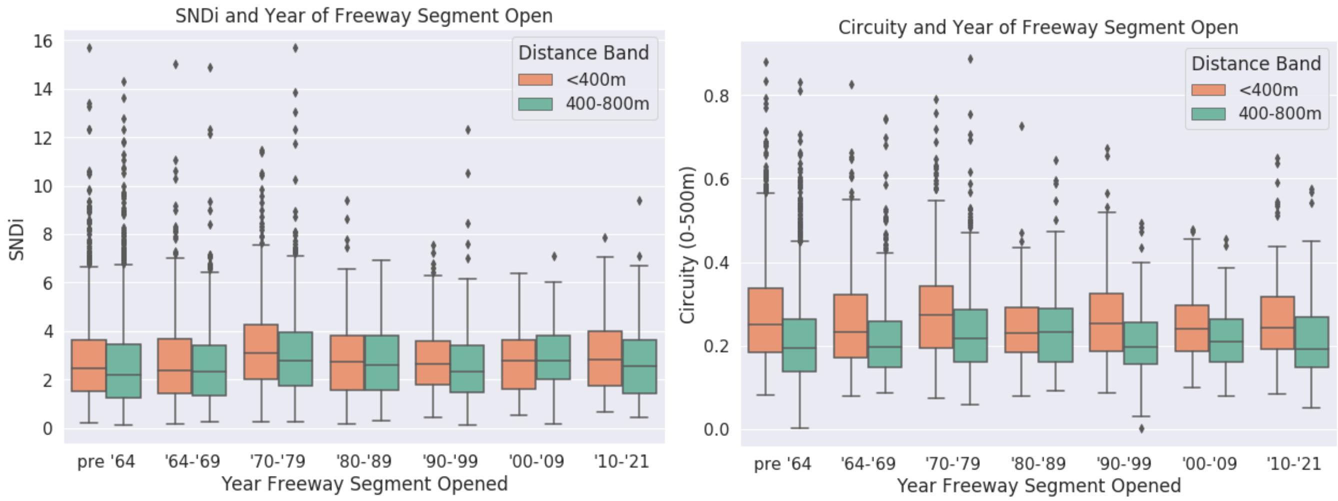


Figure 8: Association between freeways and severance over time. Each pair of bars compares the connectivity of streets in grid cells within 400m of a freeway to those in the 400-800m distance bands. The left panel indicates SNDi; the right panel indicates circuity. Data are for all urban counties in California.

Access to transit

A particular concern with street connectivity relates to access to transit (i.e., public transportation). Given that transit typically draws people who live or work within 400-800m of a stop or station (Guerra, Cervero & Tischler 2012), a disconnected street network will reduce the catchment area and in turn ridership. In places such as Los Angeles, pedestrian access may be particularly challenging given that light rail and Bus Rapid Transit stations are often in freeway medians. Access to transit is also a social justice issue, given that transit riders are disproportionately of low income, of color, and without access to a private car.

Figure 9 and Table 1 show circuity for rail stations and major bus stops in Los Angeles. In general, transit access routes are less circuitous than intersections in the county as a whole, reflecting higher levels of transit service in the denser, gridded urban core. However, access routes are slightly more circuitous than to other nearby nodes, and the inset to Figure 9 indicates wide variation even within the same neighborhood. Even rail and Bus Rapid Transit stations in freeway medians have relatively low circuity to nearby intersections. This is largely because access is via major streets as they cross under or over the freeway, providing easy access to both sides. For these stations, then, the main access concern is the quality of these crossings, as discussed below.

Figure 9: Street-network circuity at major transit stations and stops. The measure indicates the log ratio of network distance to straight-line distance from the stop/station to other nodes within 500m. The stops/stations indicated consist of rail and Bus Rapid Transit stations, together with major bus stops as defined by Los Angeles Metro. The right panel shows stops/stations located in the Palms neighborhood of Los Angeles and in Culver City, with the freeway (I-10) in blue. The impact of the freeway in increasing circuity is most evident at the bus stops in the upper right of the figure.

	Mean circuity	Median circuity
Stops/stations	0.132	0.102
Nodes within 400m of stops/stations	0.0915	0.0778
Nodes within 800m of stops/stations	0.103	0.0848
All nodes in Los Angeles County	0.193	0.153

Table 1 Circuity close to major transit stops and stations. Paths to rail stations and major bus stops are slightly more circuitous than to other nearby nodes, although less circuitous compared to Los Angeles County as a whole. Circuity indicates the ratio of Euclidean to network distance from a given node (e.g. the closest intersection to a bus stop) to all other nodes within a 0-500m radius.

Freeway crossings

Distance between crossings

While the SNDi and circuity measures discussed above measure the connectivity of a street network as a whole, the distance between crossings (shown for Los Angeles County in Figure 10) is a direct indication of the extent to which a freeway imposes a barrier. The less frequent the crossings, the greater the barrier effect. In some cases, crossings are few and far between because there is no reason to cross – for example, where a freeway runs through or alongside an uninhabited area. However, even where development occurs on both sides of the freeway, there is considerable variation in the distance between crossings. In downtown Los Angeles, many if not most of the local streets bridge the freeway, but this is not the case elsewhere in the county or state. [These patterns are similar when excluding freeway on- and off-ramps.]

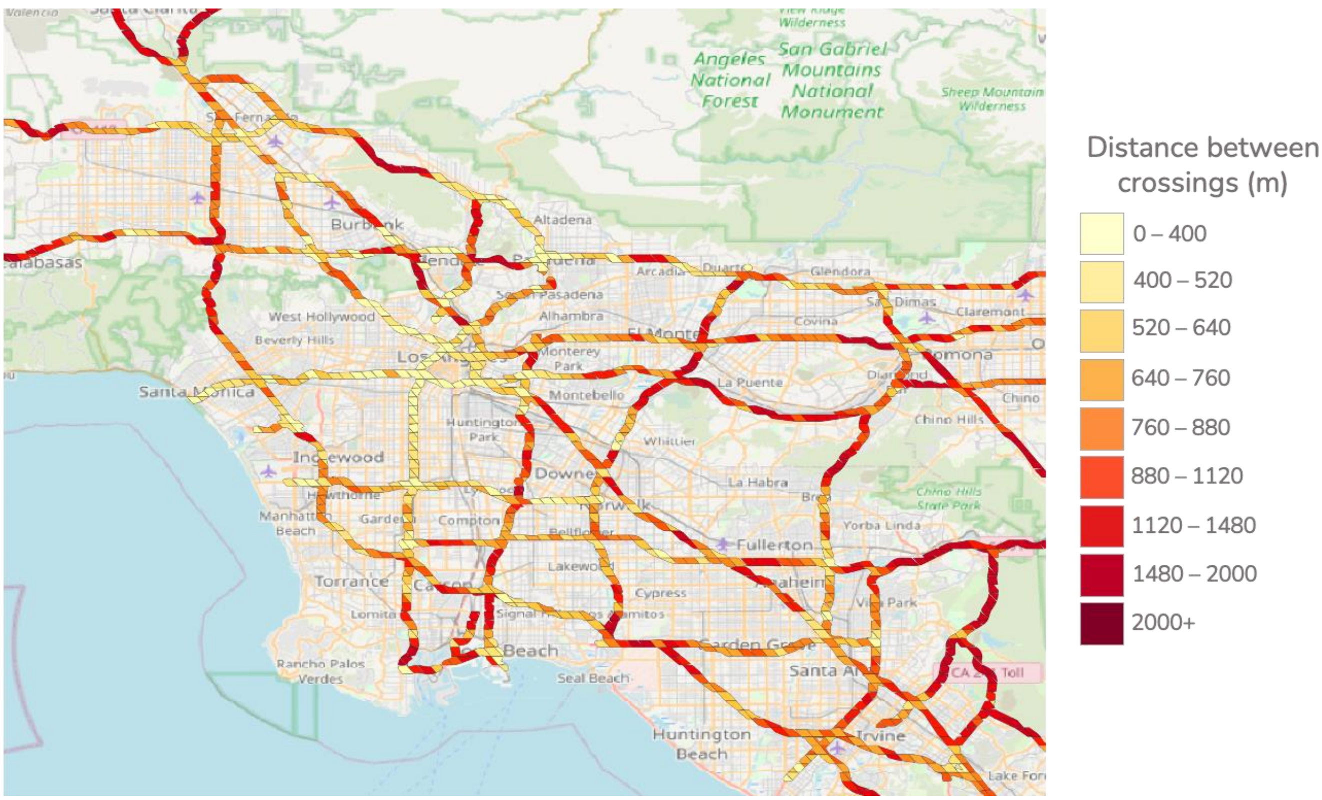


Figure 10: Distance between crossings, Los Angeles

Crossing quality

The analysis above treats all crossings equally, whether as part of our broader measures of street connectivity or through our more focused analysis of the distance between crossings. Here, we explore the variation in the quality of these crossings for pedestrians and cyclists, using the audit methodology described in the Methods section.

Our average score for walkways is 2.5, i.e. at the midpoint of our 1 (worst) to 4 (best) rating scale (Figure 11). Entrance and exit ramps have a mean score of 2.7, and bicycle facilities 2.0. Given that the quantitative scale is arbitrary, these findings are most useful in two ways. First, there is a wide distribution, meaning that some crossings are functionally unusable or pose hazards. While most (55%) of crosswalks across entrance and exit ramps had pedestrian signals, others lacked even painted crossing markings. While sidewalks were almost always present, many walkways lacked a buffer or guardrail between pedestrians and high-volume, high-speed motor traffic, and only 13% of crossings featured dedicated bicycle lanes. In short, not all of the crossings that physically exist are appealing or even usable by pedestrians and cyclists, meaning that our measures of connectivity presented above can be interpreted as an upper bound or best-case scenario.

	Walkway	Ramps	Bicycle facilities	Composite
Average score	2.48	2.72	2.03	2.40
Distri-bution				

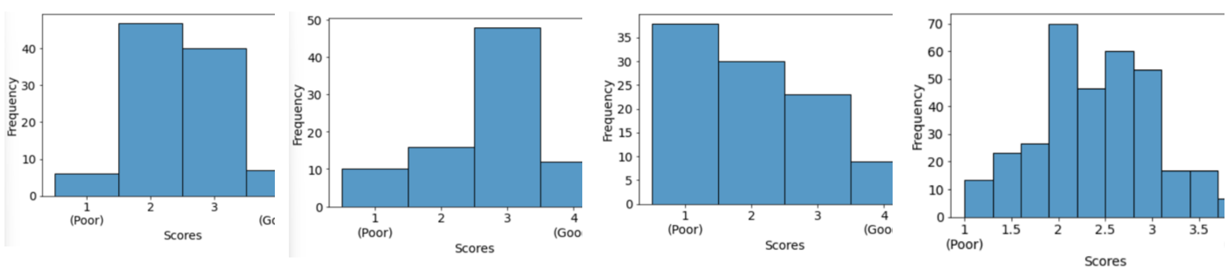


Figure 11: Score summaries and distributions for the quality of freeway crossings

Significance of crossings

The importance of crossing quality is amplified because of their sparseness; if there are long distances between crossings (as discussed above), there may not be a less-trafficked alternative nearby. We examine this formally through removing the 41 crossings that receive the lowest rating (a "1") in any category from the road network, and recomputing our SNDi and circuity measures (see Figure 12 for an example).

In the grid cells where crossings that are removed, mean SNDi increases from 2.6 to 4.2, while mean circuity doubles from 0.22 to 0.44. Thus, the effect of removing crossings is larger than the barrier impact of the freeway itself (compare with Figure 7). Because the freeway severs some streets, those that remain become disproportionately important for connectivity. Compounding the problem, motor vehicles are funneled on to a smaller number of streets that cross the freeway, which tends to further diminish the quality of those crossings for pedestrians, exposes pedestrians and bicyclists to higher levels of air pollution, and increases their risk of death or injury from a collision. A corollary is that adding or improving even a small number of crossings can make a large difference to connectivity and accessibility.

Moreover, these results represent a lower bound estimate of the impact of crossing quality, because only one crossing is removed in each grid cell. In the example in Figure 12, the crossing 800m to the west of the one removed is of similarly poor quality (no bicycle lane and a narrow, unbuffered sidewalk next to six traffic lanes), while the one 350m to the east has walkways blocked by homeless encampments.

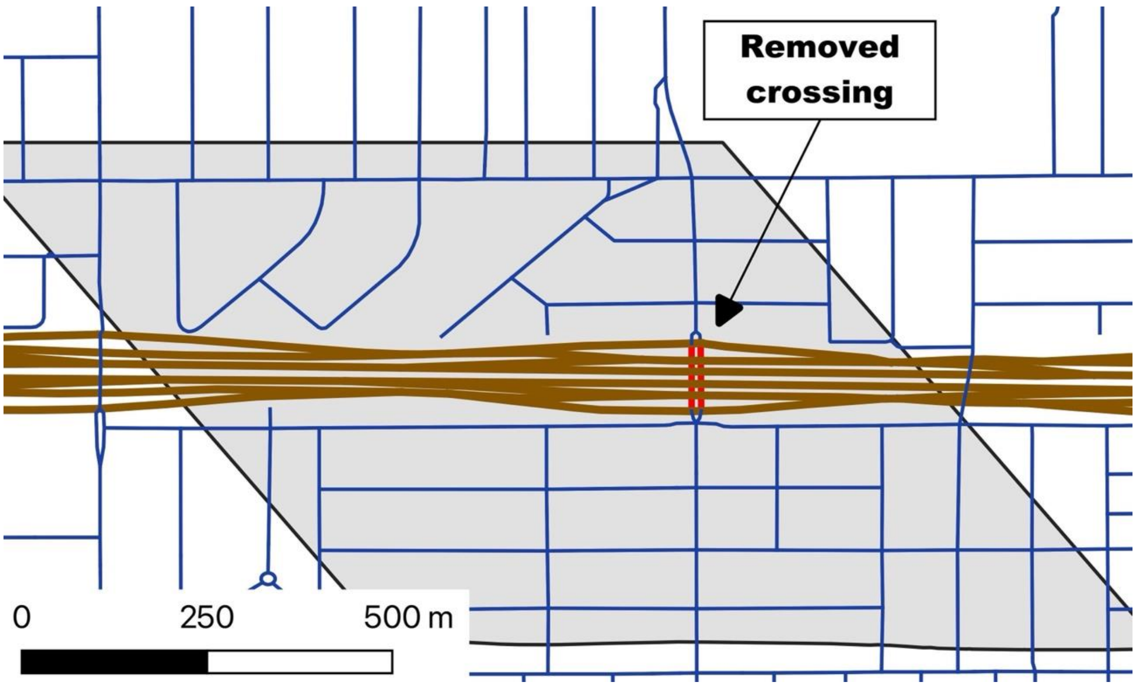
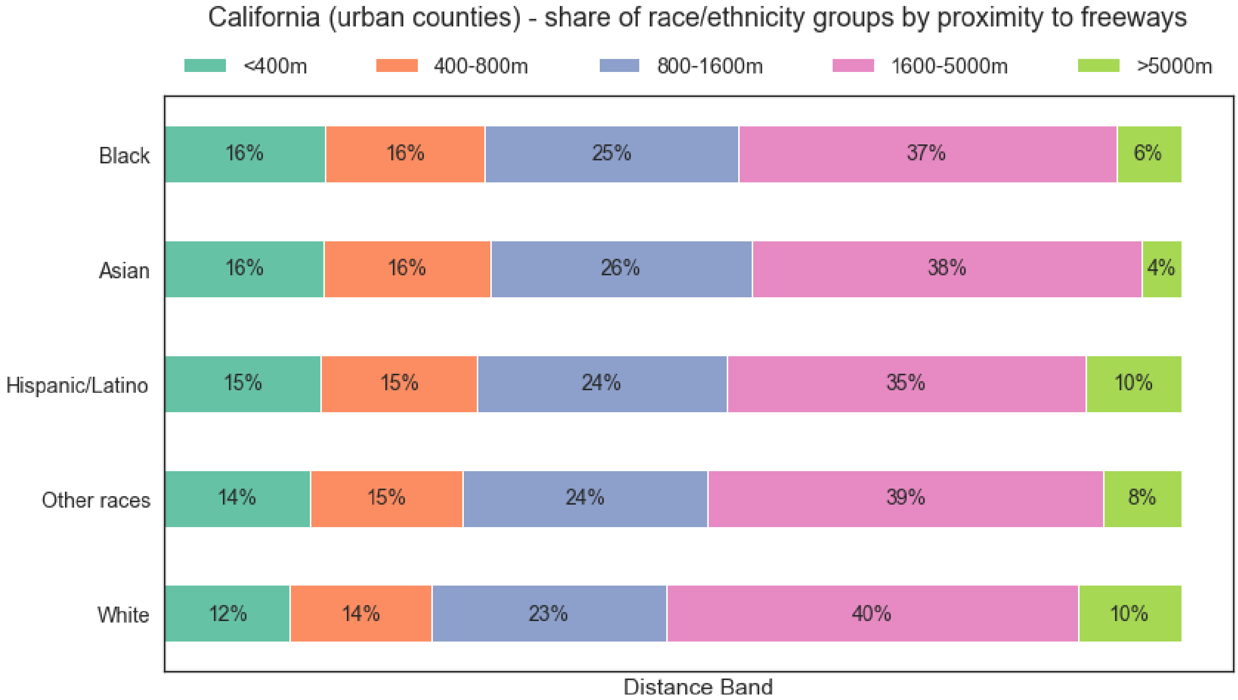


Figure 12: Recalculation of street connectivity after removing poor-quality crossings

Environmental justice and connectivity

We now consider the links between street connectivity and environmental justice. People of color are more likely to live closer to a freeway, although the differences are modest. In urban counties in California, 12% of non-Hispanic white people live within 400m of a freeway, compared to 15%-16% of Black, Asian, and Latino people (Figure 13). This has implications for exposure to noise and air pollution, but does it also translate into reduced street connectivity? That is, do our measures of connectivity – SNDi, circuity, distance between crossings, and crossing quality – vary with the racial demographics of a neighborhood?



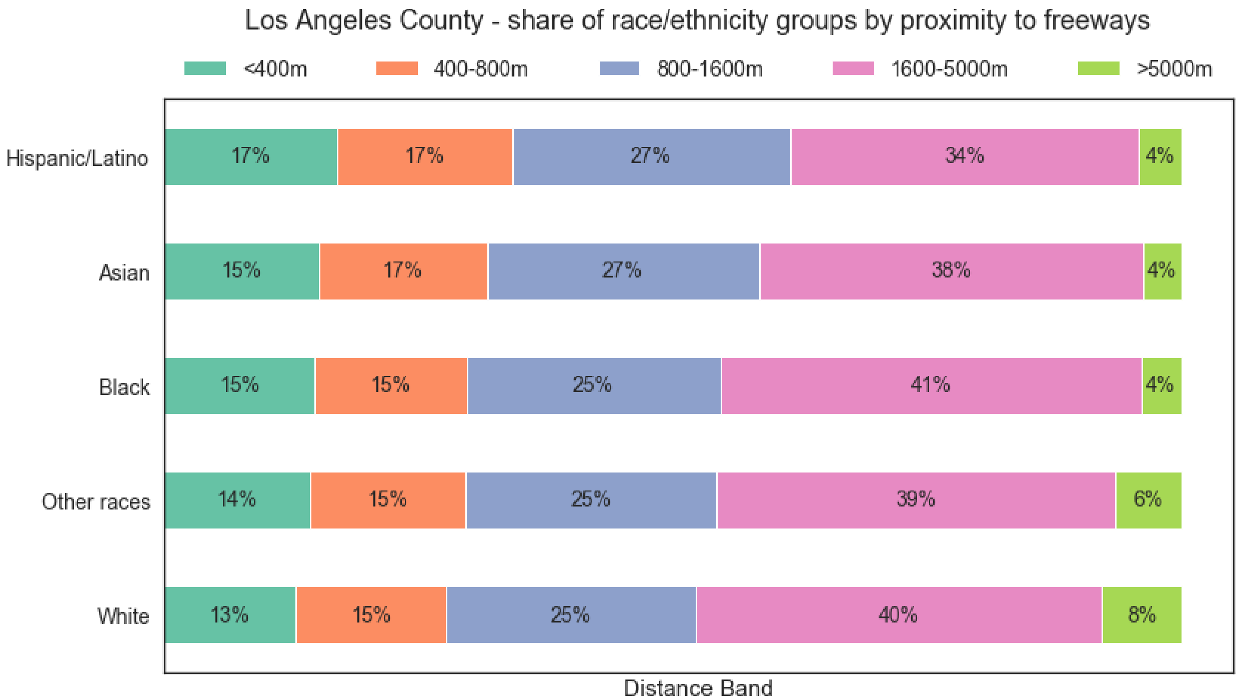


Figure 13: Share of population by race/ethnicity by proximity to freeways. Data source: Census 2020. All urban counties in California (top) and Los Angeles County (bottom).

We use regression analysis to examine these linkages. Specifically, we estimate Bayesian hierarchical models using Stan open-source software (Carpenter et al. 2017), in order to allow the effects of freeways and race to vary across counties. The modeling framework allows for partial pooling; the estimated coefficients for each county draw on information from other counties, allowing for more precise estimates particularly in the case of smaller counties with fewer observations. Each observation is a grid cell within 800m of a freeway, and we control for population density (linear and squared), slope (linear and squared), and year of freeway opening, and have separate intercepts to control for unobserved county-specific characteristics. Our coefficients of interests for the largest 20 counties are shown in Figure 14. In order to facilitate comparisons, the coefficients are standardized, and so represent the effect of a one-standard deviation change in each predictor variable (e.g. percent non-white) in terms of a standard deviation change in the outcome variable.

The left columns show how SNDi (panel A) and circuity (panel B) vary between cells that are within 400m of a freeway and our control group of cells in the 400-800m distance band. Proximity to freeways has no consistent effect on connectivity, after controlling for slope, population density, and other factors. The effect on SNDi is in fact negative, while the effect on circuity varies across counties. The center panels, meanwhile, show that connectivity is typically greater in grid cells with more people of color. Both of these results are somewhat counterintuitive, but may reflect the locations chosen for freeway routing as much as the effects of the freeways themselves.

The right panels show how these two variables interact. In largely white neighborhoods, freeways are associated with little change or even increased street connectivity. In neighborhoods of color, in contrast, freeway proximity is associated with reduced connectivity (circuity and SNDi), particularly in the largest counties. Thus, environmental injustices manifest themselves in the differential impacts of freeways in neighborhoods of different racial demographics.

One possible explanation for these injustices could be differences in the provision of crossings. However, Figure 15 shows little variation between the distance between freeway crossings and race. Here, however, we lack a comparison group of grid cells that are 400-800m from a freeway (by definition, these grid cells have no crossings). Instead, we are comparing across freeway-adjacent grid cells with different racial demographics, and so our ability to implicitly control for other neighborhood factors and identify the impacts of race are more limited. The same is true for the association between race and crossing quality; the results (not shown) also indicate little relationship, but our analysis here is further limited by the small sample size of 100 crossings, most of which are in communities of color (Figure A-1). Similarly, the smaller sample size limits our ability to investigate whether crossing quality has improved in more recently constructed freeways.

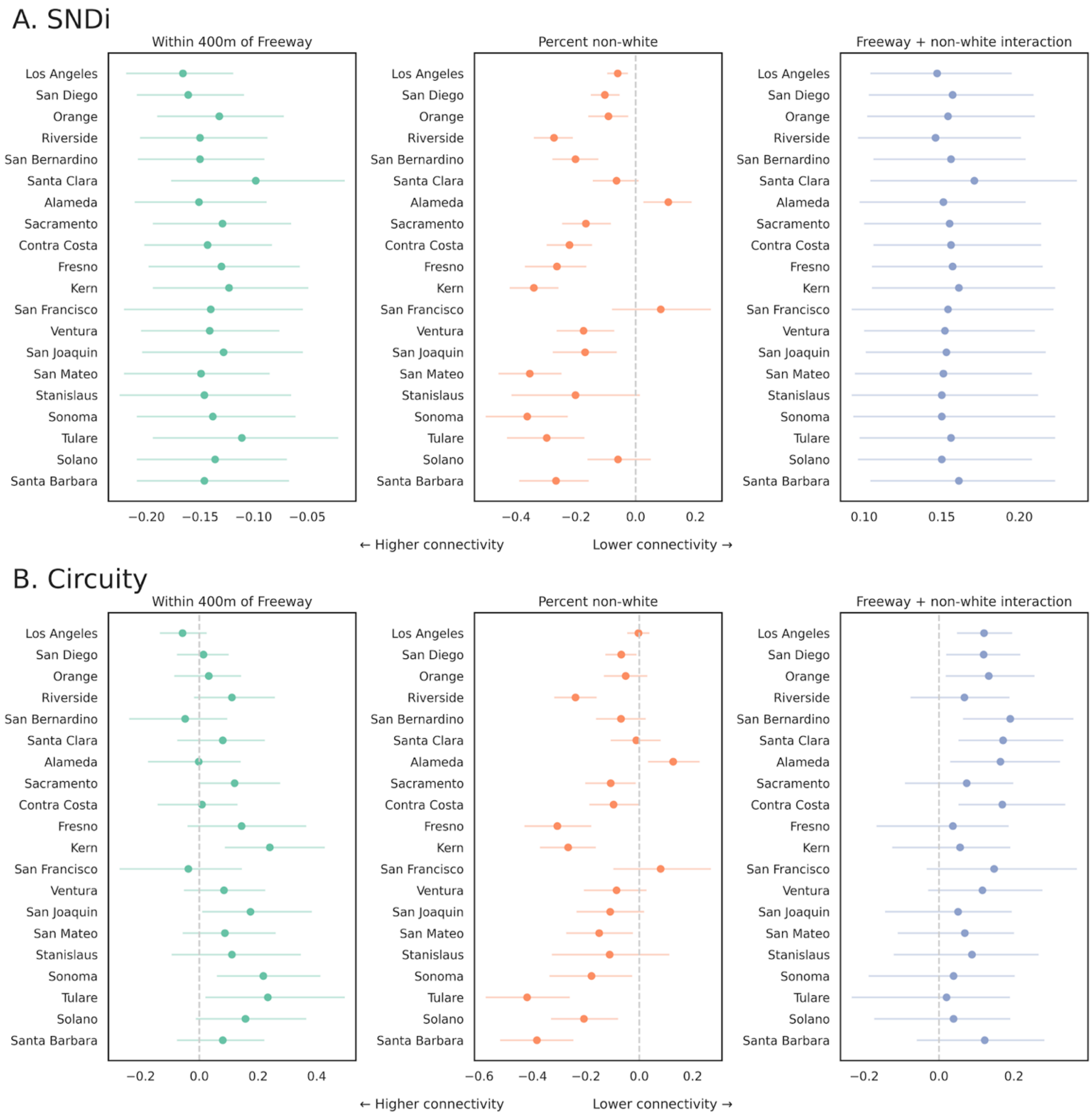


Figure 14: Regression coefficients. The dependent variables are SNDi (top) and circuity (bottom). The Bayesian hierarchical model shows how the estimated effect of freeway proximity, race, and the interactions between the two vary by county (the 20 largest counties by population are shown).

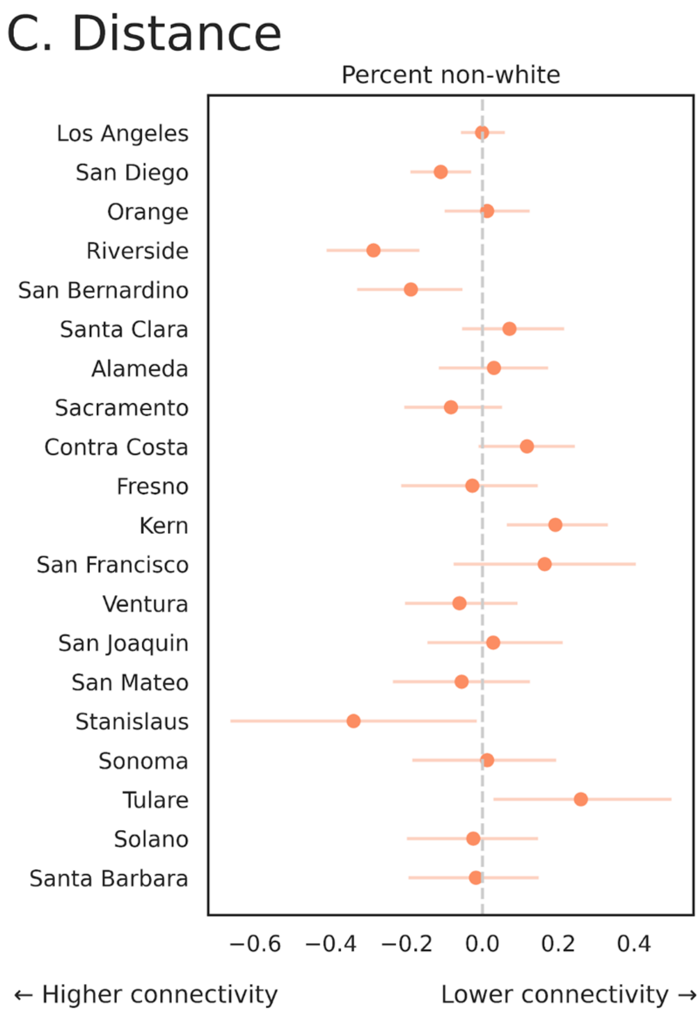


Figure 15: Regression coefficients for distance between crossings. The same Bayesian hierarchical model is used as shown in Figure 14. Because all our observations are grid cells that intersect a freeway, the impact of the freeway and the interaction with race cannot be estimated.

Conclusions

The impacts of freeways on street connectivity have long been recognized. These severance and barrier effects are particularly important for pedestrians and cyclists, who are more sensitive to the increased travel distances as well as non-physical barriers such as noise and air pollution. However, most studies to date have been limited to specific neighborhoods. Here, we provide the first large-scale analysis of severance using algorithms to quantify street connectivity for California. Statewide, we analyze three measures of connectivity – a composite index (SNDi), one of its component measures (circuity), and, along freeways, the distance between crossings (under- and overpasses). In Los Angeles County, we also analyze the quality of a sample of 100 crossings for pedestrians and cyclists.

In many places, freeways do reduce connectivity, particularly where they run through previously established urban areas. Many otherwise-continuous local streets dead-end either side of the freeway. However, the effects are surprisingly heterogeneous, and hard to isolate because freeways are often built though the parts of cities with the most connected streets – for example, on flatter ground. To isolate causal effects, future analysis would ideally digitize the historical street network prior to freeway construction, in order to enable a before-after comparison of connectivity (see Figure 5 for a small-scale example).

In some places (such as downtown Los Angeles), there are frequent crossings via local streets and dedicated bicycle/pedestrian bridges. In other places, there is little reason to cross the freeway, as one or perhaps both sides are uninhabited. But in a third category of places, crossings are limited to streets with on and off ramps, which means both that the distances between crossings (and thus the detours) are greater, and that walkers and cyclists must contend with high-volume, high-speed traffic that is funneled on to a small number of streets. These crossings are typically built with freeway access as the main consideration, not safety and connectivity for pedestrians and cyclists.

In places where crossings are sparse, connectivity is thus even poorer than SNDi or circuity would suggest. Our audit in Los Angeles County finds that many crossings offer a poor experience for pedestrians and cyclists, and in some cases may be functionally unusable for non-motorized road users. The combination of fast-moving traffic at on- and-off-ramps, high traffic volumes, and minimal infrastructure such as wide sidewalks or bicycle lanes makes for an uncomfortable or even hazardous experience. Moreover, the sparsity of crossings means that there is little reasonable alternative in some neighborhoods; removing the "poor" crossings more than doubles circuity in our analysis.

Severance impacts are most pronounced in communities of color. It is hard to isolate any specific causal mechanism, and as with many manifestations of environmental injustices, several mechanisms may be at play (Banzhaf et al. 2019). We might speculate whether racial bias in freeway siting (e.g. Ramirez et al. 2022) also permeates design decisions, or whether structural racism is key: less walkable neighborhoods reduce housing prices that in turn lead to lower-income people of color seeking out more affordable housing. But environmental injustices are fundamentally about disparate impacts regardless of whether those are brought about by intentionally discriminatory practices, and those disparities certainly exist in the case of severance.

What do our findings imply for planning and policy? For newly constructed freeways, severance can be reduced by maintaining the continuity of at least some local street connections, especially where no on- or off-ramp is provided. When crossings would otherwise be few, each additional crossing may have a large effect on connectivity. For existing freeways, building new crossings (e.g. pedestrian or bicycle bridges) can be valuable, although it can be challenging to design them in a way that provides direct routes and real and perceived safety. But the poor quality of many existing crossings points the way to a lower-cost, more quickly implemented approach: widening sidewalks, adding a buffer between pedestrians and moving traffic, and providing signals or shorter turn radii to slow traffic exiting or entering a freeway. Our analysis indicates a data-driven way to prioritize such improvements, that can take into account environmental justice and access to transit as well as overall street connectivity.

Efforts to address severance, however, should not neglect consideration of the – more important – impacts of freeways on air and noise pollution, which are also concentrated in communities of color. Rather than addressing the negative consequences of freeways in a piecemeal fashion through (say) pedestrian bridges, sound barriers, and supplying air filters to nearby households, planners and policy makers might look to cities such as Boston and Oslo that are undergrounding road infrastructure, or to Seoul and San Francisco that have started to remove some freeways altogether.

References

Anciaes, Paulo, and Peter Jones. 2020. "A Comprehensive Approach for the Appraisal of the Barrier Effect of Roads on Pedestrians." *Transportation Research Part A: Policy and Practice* 134:227–50. doi: 10.1016/j.tra.2020.02.003.

Anciaes, Paulo, Peter Jones, and Jennifer S. Mindell. 2016. "Community Severance: Where Is It Found and at What Cost?" *Transport Reviews* 36(3):293–317. doi: 10.1080/01441647.2015.1077286.

Appleyard, Donald, M. Sue Gerson, and Mark Lintell. 1981. *Livable Streets*. Berkeley: University of California Press.

Banzhaf, Spencer, Lala Ma, and Christopher Timmins. 2019. "Environmental Justice: The Economics of Race, Place, and Pollution." *Journal of Economic Perspectives* 33(1):185–208. doi: 10.1257/jep.33.1.185.

Barrington-Leigh, Christopher, and Adam Millard-Ball. 2017. "More Connected Urban Roads Reduce US GHG Emissions." *Environmental Research Letters* 12(4):044008. doi: 10.1088/1748-9326/aa59ba.

Barrington-Leigh, Christopher, and Adam Millard-Ball. 2019. "A Global Assessment of Street-Network Sprawl." *PLoS ONE* 14(11):e0223078. doi: 10.1371/journal.pone.0223078.

Baum-Snow, N. 2007. "Did Highways Cause Suburbanization?" *The Quarterly Journal of Economics* 122(2):775–805. doi: 10.1162/qjec.122.2.775.

Bayor, Ronald H. 1988. "Roads to Racial Segregation. Atlanta in the Twentieth Century." *Journal of Urban History* 15(1):3–21.

Biljecki, Filip, and Koichi Ito. 2021. "Street View Imagery in Urban Analytics and GIS: A Review." *Landscape and Urban Planning* 215:104217. doi: 10.1016/j.landurbplan.2021.104217.

Boarnet, Marlon G., Kristen Day, Mariela Alfonzo, Ann Forsyth, and Michael Oakes. 2006. "The Irvine–Minnesota Inventory to Measure Built Environments." *American Journal of Preventive Medicine* 30(2):153-159.e43. doi: 10.1016/j.amepre.2005.09.018.

Bosselmann, Peter, Elizabeth Macdonald, and Thomas Kronemeyer. 1999. "Livable Streets Revisited." *Journal of the American Planning Association* 65(2):168–80. doi: 10.1080/01944369908976045.

Bullard, Robert D., and Glenn S. Johnson, eds. 1997. *Just Transportation: Dismantling Race and Class Barriers to Mobility.* Gabriola Island, BC: New Society Publishers.

Carpenter, Bob, Andrew Gelman, Matt Hoffman, Daniel Lee, Ben Goodrich, Michael Betancourt, Michael A. Brubaker, Jiqiang Guo, Peter Li, and Allen Riddell. 2017. "Stan: A Probabilistic Programming Language." *Journal of Statistical Software* 76(1):1–32. doi: 10.18637/jss.v076.i01.

Cervero, R. 2002. "Induced Travel Demand: Research Design, Empirical Evidence, and Normative Policies." *Journal of Planning Literature* 17(1):3–20.

Chakraborty, Jayajit. 2006. "Evaluating the Environmental Justice Impacts of Transportation Improvement Projects in the US." *Transportation Research Part D: Transport and Environment* 11(5):315–23. doi: 10.1016/j.trd.2006.06.003.

Dottle, Rachel, Laura Bliss, and Paulo Robles. 2021. “What It Looks Like to Reconnect Black Communities Torn Apart by Highways.” *CityLab,* July 28.

Duranton, Gilles, and Matthew A. Turner. 2011. “The Fundamental Law of Road Congestion: Evidence from US Cities.” *American Economic Review* 101(6):2616–52. doi: 10.1257/aer.101.6.2616.

van Eldijk, Job. 2019. “The Wrong Side of the Tracks: Quantifying Barrier Effects of Transport Infrastructure on Local Accessibility.” *Transportation Research Procedia* 42:44–52. doi: 10.1016/j.trpro.2019.12.005.

van Eldijk, Job, Jorge Gil, and Lars Marcus. 2022. “Disentangling Barrier Effects of Transport Infrastructure: Synthesising Research for the Practice of Impact Assessment.” *European Transport Research Review* 14(1):1. doi: 10.1186/s12544-021-00517-y.

Emond, Catherine R., and Susan L. Handy. 2012. “Factors Associated with Bicycling to High School: Insights from Davis, CA.” *Journal of Transport Geography* 20(1):71–79. doi: 10.1016/j.jtrangeo.2011.07.008.

Fleischer, Matthew. 2020. “Want to Tear down Insidious Monuments to Racism and Segregation? Bulldoze L.A. Freeways.” *Los Angeles Times,* June 24.

Forkenbrock, David J., and Lisa A. Schweitzer. 1999. “Environmental Justice in Transportation Planning.” *Journal of the American Planning Association* 65(1):96–112. doi: 10.1080/01944369908976036.

Furth, Peter G., Maaza C. Mekuria, and Hilary Nixon. 2016. “Network Connectivity for Low-Stress Bicycling.” *Transportation Research Record: Journal of the Transportation Research Board* 2587(1):41–49. doi: 10.3141/2587-06.

Garcia-López, Miquel-Àngel. 2019. “All Roads Lead to Rome … and to Sprawl? Evidence from European Cities.” *Regional Science and Urban Economics* 79:103467. doi: 10.1016/j.regsciurbeco.2019.103467.

Gordon, Wyatt. 2021. “Could Biden’s Infrastructure Bill Help Heal the Scars Highways Created?” *Streetsblog,* December 13.

Grisolía, José M., Francisco López, and Juan de Dios Ortúzar. 2015. “Burying the Highway: The Social Valuation of Community Severance and Amenity.” *International Journal of Sustainable Transportation* 9(4):298–309. doi: 10.1080/15568318.2013.769038.

Guerra, Erick, Robert Cervero, and Daniel Tischler. 2012. “Half-Mile Circle: Does It Best Represent Transit Station Catchments?” *Transportation Research Record* 2276:101–9. doi: 10.3141/2276-12.

Haddad, Paul, and Patt Morrison. 2021. *Freewaytopia: How Freeways Shaped Los Angeles*. Solana Beach: Santa Monica Press.

Handy, Susan. 2003. “Amenity and Severance.” Pp. 117–39 in *Handbook of Transport and the Environment*, edited by D. A. Hensher and K. J. Button. London: Elsevier.

Kim, David. 2020. *Statement on Racial Equity, Justice and Inclusion in Transportation.* https://calsta.ca.gov/press-releases/2020-06-12-statement-on-racial-equity

Kurka, Jonathan M., Marc A. Adams, Carrie Geremia, Wenfei Zhu, Kelli L. Cain, Terry L. Conway, and James F. Sallis. 2016. "Comparison of Field and Online Observations for Measuring Land Uses Using the Microscale Audit of Pedestrian Streetscapes (MAPS)." *Journal of Transport & Health* 3(3):278–86. doi: 10.1016/j.jth.2016.05.001.

Lieb, Jacob, et al. 2019. *Aviation/96th Street First/Last Mile Plan.* Los Angeles County Metropolitan Transportation Authority (Metro), 22 March 2019.

McEntee, Jesse C., and Yelena Ogneva-Himmelberger. 2008. "Diesel Particulate Matter, Lung Cancer, and Asthma Incidences along Major Traffic Corridors in MA, USA: A GIS Analysis." *Health & Place* 14(4):817–28. doi: 10.1016/j.healthplace.2008.01.002.

Mindell, Jennifer S., and Paulo R. Anciaes. 2020. "Transport and Community Severance." Pp. 175–96 in *Advances in Transportation and Health*. Elsevier.

Nimegeer, Amy, Hilary Thomson, Louise Foley, Shona Hilton, Fiona Crawford, and David Ogilvie. 2018. "Experiences of Connectivity and Severance in the Wake of a New Motorway: Implications for Health and Well-Being." *Social Science & Medicine* 197:78–86. doi: 10.1016/j.socscimed.2017.11.049.

Ramirez, Andres F., Emmanuel Proussaloglou, Anastasia Loukaitou-Sideris, and Jacob L. Wasserman. 2022. "Exposing Freeway Inequalities in the Suburbs: The Cases of Pasadena and Pacoima." Working paper.

Rothstein, Richard. 2018. *The Color of Law: A Forgotten History of How Our Government Segregated America.* New York: Liveright.

Rowangould, Gregory M. 2013. "A Census of the US Near-Roadway Population: Public Health and Environmental Justice Considerations." *Transportation Research Part D: Transport and Environment* 25:59–67. doi: 10.1016/j.trd.2013.08.003.

Schweitzer, Lisa, and Abel Valenzuela. 2004. "Environmental Injustice and Transportation: The Claims and the Evidence." *Journal of Planning Literature* 18(4):383–98. doi: 10.1177/0885412204262958.

Steinmetz-Wood, Madeleine, Kabisha Velauthapillai, Grace O'Brien, and Nancy A. Ross. 2019. "Assessing the Micro-Scale Environment Using Google Street View: The Virtual Systematic Tool for Evaluating Pedestrian Streetscapes (Virtual-STEPS)." *BMC Public Health* 19(1):1246. doi: 10.1186/s12889-019-7460-3.

White House. 2021. *Press Briefing by Principal Deputy Press Secretary Karine Jean-Pierre and Secretary of Transportation Pete Buttigieg.* November 8, 2021. https://www.whitehouse.gov/briefing-room/press-briefings/2021/11/08/press-briefing-by-principal-deputy-press-secretary-karine-jean-pierre-and-secretary-of-transportation-pete-buttigieg/

Appendix

Calculation of distances between crossings

We compute the distance between freeway crossings (i.e., over- or underpasses) as follows:

1. In PostGIS, we merge (union) all freeway edges. We then split them where they intersect a crossing, so that the length of each freeway edge represents the distance between adjacent crossings.

2. We aggregate to grid cells by taking the distance between crossings for each edge that intersects that grid cell, weighted by the edge lengths within that grid cell. We use a similar weighting to aggregate to freeway segments (e.g I-5 or CA-99).

For each grid cell x that intersects edges $(k_1, \dots, k_n)$, the distance between crossings can be calculated as:

$$Distance_x = \frac{\sum_{k_i} len(k_i) * len(x, k_i)}{\sum_{k_i} len(x, k_i)}$$

where $len(x)$ represents the length of the edge x and $len(x, y)$ represents the length of the intersection of the geometries of x and y.

While for clarity, we express our results in terms of the distance between crossings, a more meaningful measure for a pedestrian is likely to be the average or expected distance to the closest crossing. However, these two measures are linearly related—the distance between crossings is four times the average distance to the closest crossing for an infinite set of random points on that freeway edge, as derived as follows. We calculate this for a straight line on the x-axis that has endpoints at (0,0) and (y,0), and a random point located at (x,0) along this line:

$$D(x) = min(x, y - x)$$

$$= \frac{1}{y}\left(\int_0^{y/2} x\,dx + \int_{y/2}^{y} (y - x)\,dx\right)$$

$$= \frac{1}{y}\left(\frac{y^2}{8} + \left(\frac{y^2}{2} - \frac{y^2}{2} + \frac{y^2}{8}\right)\right) = \frac{1}{y}\frac{y^2}{4}$$

$$= \frac{y}{4}$$

Note: This distance would be accurate for any line in geometry, even a curved line. However, in a real-world situation, these edges are not "one point" thick. As the length of each "side" of these edges varies when they are curved, this measure is an approximation of the average distance to the closest crossing.

Freeway Crossing Quality Audit

Table A-1 shows our criteria to assess crossing quality in three categories: the pedestrian walkway, crossings of entrance and/or exit ramps (if they exist), and bicycle facilities. Note that our criteria are limited to those that are feasible to assess via Google Street View. Figure A-1 shows the location of each sampled crossing (red markers), along with the racial demographics of each grid cell.

Table A-1: Scoring criteria to assess freeway crossing quality

	4	3	2	1
Pedestrian walkway	> 8ft unobstructed sidewalk OR pedestrian bridge or tunnel with direct[1] path of travel	6-8ft mostly unobstructed sidewalk; minor sidewalk damage or debris present OR bridge or tunnel with indirect path of travel	4-6ft obstructed[2] sidewalk OR no walkway	Obstructions render walkway unusable OR no sidewalk AND no walkway away from traffic
	Buffer with street parking AND trees	Buffer with street parking OR trees	Empty buffer OR guardrail only	No buffer or guardrail
	Mostly shaded	Mostly shaded	Little to no shade	Little to no shade
	Continuous street lighting	Continuous street lighting	Little to no street lighting	Little to no street lighting
	Speed limit < 25mph	Speed limit 25-30mph	Speed limit 35mph	Speed limit > 35mph
	≤ 2 travel lanes	3-4 travel lanes	≥ 5 travel lanes	≥ 5 travel lanes
Ramps	No ramp; street crossing connects side streets	Ramp	Ramp	Ramp
	Marked designated pedestrian crossing	Marked designated pedestrian crossing	Crossing is unmarked but includes curb cuts	No safe crossing OR crossings prohibited
	Stop signs OR traffic light with pedestrian signal	Yield signs OR traffic lights without pedestrian signal	Traffic lights without pedestrian signal	No signs
	Curb extensions to reduce turning radius	Wide corner radius	Wide corner radius	Wide corner radius
	Short crossing distance (≤ 2 lanes) OR median refuge	Short crossing distance (≤ 2 lanes) OR median refuge	No median refuge, AND > 2 lanes to cross	No median refuge, AND > 2 lanes to cross
Bicycle facilities	Exclusive right of way for bicycles[3] via physical separation from traffic, OR traffic is ≤ 2 lanes and ≤ 25 mph	Dedicated continuous bicycle lane along street, OR traffic is ≤ 2 lanes and 30-35mph	No dedicated bikeway, AND traffic is ≥ 3 lanes and 35mph	No dedicated bikeway, AND traffic is ≥ 5 lanes or > 35mph

[1] i.e. not containing switchbacks that lengthen time spent walking
[2] by informal shelters, debris, or sidewalk damage; street furniture excluded
[3] or shared bicycle and pedestrian path

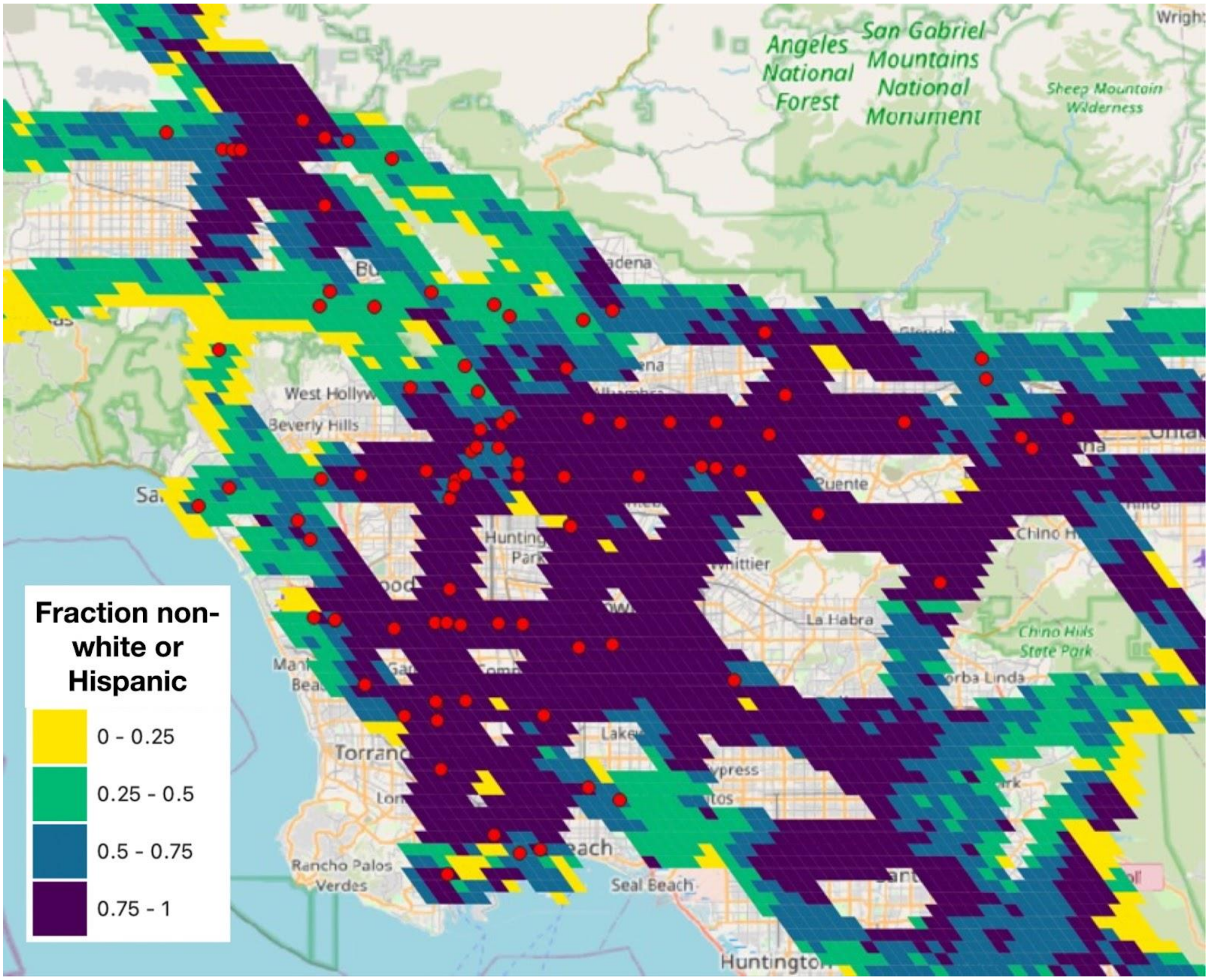


Figure A-1. Locations of sampled crossings. *Red markers show the locations of each crossing includes in the audit.*