

Article

Highway as Barriers to Park Visitation: A Fixed Effects Analysis Using Mobility Data

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Abstract

Urban parks provide critical benefits for public health, mental well-being, and social connection. However, inequities in park access and use persist, particularly among socially and economically vulnerable populations. While previous studies have established that segregation and social vulnerability each contribute to uneven park access, little is known about how these two forces interact to shape real visitation patterns. This study addresses this research gap and answers the research question: How does highway segregation relate to differences in the different aspects of social vulnerability in influencing park access across Austin's east–west divide? SafeGraph mobility data from 2019 and the Social Vulnerability Index (SVI), which included four themes (i.e., socioeconomic status, household composition, minority status and language, and housing and transportation characteristics), were analyzed through fixed-effects regression models for Austin, Texas. Results show that household composition and minority vulnerabilities have negative associations with park visitation, indicating that areas with more elderly, single-parent, or minority residents visit parks less frequently. Interaction terms reveal that highway segregation functions as a structural barrier that conditions the influence of social vulnerability on park use. Those associated with socioeconomic resources diminish, while the disadvantages linked to household composition and minority status intensify on the east side of I-35, reflecting the cumulative effects of segregation and infrastructural division. These findings confirm that inequities in park access are more pronounced on the east side of the I-35, consistent with the highway's role in reinforcing segregation. Efforts to strengthen connectivity represent key strategies for advancing equitable park visitation across Austin.

Keywords: highway segregation; Social Vulnerability Index (SVI); park visitation; mobility data



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1. Introduction

Urban parks are widely recognized for their contributions to physical health, mental well-being, and social cohesion. However, urban parks face growing challenges, including unequal distribution, declining maintenance, gentrification pressures, and the fragmentation of green networks caused by rapid urbanization. These challenges threaten the inclusivity and sustainability of parks as essential public goods. As a result, access to these benefits is not equally distributed, particularly for communities that experience persistent social and economic vulnerability. A growing body of research has documented disparities in park provision and use, particularly among those socially vulnerable communities [1–3].

Social vulnerability, defined by factors such as income, race, age, disability, and transportation access, influences individuals' capacity to use parks safely and consistently [4,5]. These disparities are not solely due to park availability or design but also reflect deeper structural inequalities embedded in urban planning, infrastructure, and social policy.

Among these structural drivers, urban segregation policies, including highway construction as a form of spatial segregation, play significant roles in shaping who can access and benefit from urban green spaces. Urban segregation refers to the way major transportation infrastructure has been used to divide communities, often reinforcing racial and economic boundaries in cities [4]. For instance, the construction of the I-35 highway in Austin, Texas, in the mid-20th century serves as a prominent example of this circumstance. The highway physically separates historically marginalized neighborhoods on the east side from wealthier, Whiter neighborhoods to the west [5]. This divide continues to impact patterns of infrastructure investment, mobility, and park access, exacerbating disparities rooted in both social vulnerability and urban segregation. Similar patterns are evident in other global cities where transport infrastructure reinforces social divides, indicating that infrastructural segregation is not a localized phenomenon but a global driver of environmental inequity [6,7]. The relationship between social vulnerability and park visitation is essential because it reveals who can truly access and benefit from urban parks and informs city planning and decision-making. Previous studies indicate that vulnerable communities have less access to urban parks. However, the extent to which highway segregation amplifies the effects of social vulnerability on park use, beyond existing neighborhood disadvantage, remains insufficiently examined.

Existing studies have examined disparities in park distribution and social barriers to use; most rely on proximity-based models, such as buffer distances, that assume geographic closeness translates into actual park engagement [8,9]. Such approaches often overlook the behavioral dimension of access and fail to capture the real-world mobility constraints and infrastructural barriers that limit visitation, especially in communities divided by highways. Traditional accessibility metrics do not account for real-world barriers such as limited pedestrian infrastructure, inadequate public transportation, and safety concerns, all of which can significantly restrict park use [9,10]. To more accurately assess usage patterns, there is a growing need for studies that move beyond assumed accessibility and instead draw on empirical measures of actual visitation behavior.

This study addresses these gaps by introducing a longitudinal framework that integrates mobility big data with social vulnerability metrics to measure actual visitation rather than assumed access. This research aims to (1) evaluate how different dimensions of social vulnerability influence park visitation and (2) analyze how highway segregation moderates these relationships across Austin's east–west divide. Using longitudinal mobility data and fixed-effects modeling, we compared patterns of park use across census tracts on either side of I-35. This research provides a more comprehensive understanding of how physical and personal barriers jointly influence access to urban green spaces.

This paper makes two key contributions. First, it examines highway segregation as a moderating mechanism, between social vulnerability and park visitation. It offers a new theoretical perspective that connects social structure, infrastructure, and environmental behavior. Second, it challenges traditional accessibility models by focusing on actual visitation patterns through mobility big data rather than assumed proximity-based access, providing a more accurate approach for assessing park inequities and informing urban policy.

2. Literature Review

2.1. Accessibility for Park

Access to urban parks represents a core dimension of distributional justice, which concerns the equitable allocation of environmental amenities and burdens among different social groups. Grounded in environmental justice theory, distributional justice emphasizes the fair provision and quality of parks and open spaces, as well as the social and institutional factors that determine who benefits from them [10,11]. Justice in park access extends beyond the physical presence of green spaces to include their safety, usability, and overall quality.

Empirical studies consistently demonstrate that wealthier and predominantly White neighborhoods have higher park provision, better maintenance, and more diverse recreational facilities compared to low-income and minority communities [8,12]. Such disparities are not isolated phenomena but the outcomes of urban development processes that prioritize land value and vehicular mobility over social equity, thereby generating spatial concentrations of environmental privilege and exclusion.

Accordingly, park accessibility is highly related to the outcomes of urban planning, which highlights vehicular mobility and the expansion of highway systems in American planning. This automobile-oriented pattern often fragments urban neighborhoods, reduces pedestrian connectivity, and creates physical and psychological barriers that limit equitable access to public spaces [13]. Highways exemplify how mobility-oriented infrastructure can reinforce social segregation and reduce the everyday accessibility of parks for marginalized populations [12].

2.2. Highway Segregation and Impacts for Park Visitation

Highway development has had profound impacts on society and the economy. It facilitated regional connectivity, economic growth, and suburban expansion; meanwhile, it caused negative externalities such as residential displacement and environmental degradation [14]. Highway segregation refers to the use of highway infrastructure to divide communities along racial and socioeconomic lines, particularly during the era of interstate highway expansion from the 1950s to the 1990s [14]. Rather than serving purely functional purposes, highways were routed through or around disadvantaged neighborhoods, resulting in widespread displacement, community fragmentation, and the entrenchment of spatial inequality [15]. These infrastructure decisions not only reshaped the urban physical landscape but also reinforced patterns of social segregation.

As urban infrastructure, highways continue to function as both material and symbolic barriers to public resource access. Their negative externalities, such as noise, pollution, and heavy traffic, discourage pedestrian activity and reduce the desirability of adjacent areas [16]. In terms of park accessibility, highways act as barriers by creating physical divisions in the urban fabric and signaling long-term disinvestment in marginalized areas. This contributes to both limited mobility and perceptions of exclusion from public amenities like parks.

Highways create community severance by physically fragmenting neighborhoods and limiting pedestrian connectivity [14,15,17]. Multi-lane, high-speed roads act as barriers that are difficult and unsafe to cross, particularly for socially vulnerable populations with limited mobility resources [18]. This structural divide reduces the effective accessibility of parks located across freeways, meaning that even geographically proximate green spaces may remain practically unreachable. In this way, community severance amplifies mobility constraints, disproportionately widening visitation gaps between vulnerable and more advantaged groups [19].

Beyond physical separation, highways also operate as perceptual and psychological boundaries. For vulnerable communities, freeways symbolize exclusion and reinforce social

divides [5,18], shaping how people evaluate the safety and desirability of nearby spaces [20]. Crossing a highway or visiting a park on the other side may involve heightened feelings of danger and discomfort. These perceptions form social barriers, including safety concerns, that discourage park use, even when parks are accessible in principle [21]. Moreover, the effects of motorway isolation extend to social and cultural domains. For low-income or minority residents, highways often mark the limits of social belonging, reducing their sense of safety and inclusion in parks located across these divides [11]. Culturally, such infrastructural separations disrupt community identity and collective attachment to place, diminishing motivation for leisure or recreation in spaces perceived as “not for us” [22].

Highways often generate surrounding disamenities, including noise, pollution, reduced property values, and a general perception of long-term disinvestment [14,17]. Parks located adjacent to highways may therefore suffer from lower quality, fewer amenities, and limited maintenance investment [23,24]. For socially vulnerable groups who already face constrained mobility, these amenities and quality further diminish the appeal and usability of such parks, leading to inequities in green space engagement [11,12].

2.3. Social Vulnerability and Park Visitations

Social vulnerability encompasses a set of individual and community characteristics that influence the capacity to respond to environmental and social stressors [16]. This definition has been widely recognized as a determinant of urban park use. Communities with higher levels of vulnerability, characterized by low income, racial/ethnic minority status, older age, disability, and lack of private vehicle access, are less likely to engage in park-based recreation compared to more advantaged groups, even when geographic proximity to green space is similar [21,24].

Previous studies have demonstrated that socially vulnerable populations tend to underutilize public parks because vulnerability constrains both the capacity and the opportunity to participate in leisure activities [20]. This evidence suggests that social vulnerability has a negative influence on actual visitation, underscoring that access, measured purely by distance or supply, does not guarantee equitable use [25].

Several factors have been proposed to explain why vulnerable communities have lower park visitation. First, deficits in park quality are prevalent in parks serving disadvantaged neighborhoods; these facilities often provide fewer recreational features, less programming, and poorer maintenance conditions, which discourage use [10,25]. Second, accessibility constraints such as limited car ownership and weak transit connectivity reduce access to higher-quality parks located beyond walking distance, constraining discretionary trips [26]. Third, social barriers, including safety concerns, further discourage use [27]. Fear of crime, harassment, and traffic danger can lower the likelihood of visits, particularly for women, children, and the elderly, while experiences of discrimination, lack of culturally relevant programming, and weak social cohesion exacerbate exclusion among minoritized groups [28]. Taken together, these mechanisms illustrate that the relationship between social vulnerability and park visitation is mediated by physical, accessibility, and social barriers, factors rather than geographic distance alone.

To operationalize these mechanisms, this study clarifies the four themes of the Social Vulnerability Index (SVI): socioeconomic status, household composition and disability, minority status and language, and housing and transportation. Each theme reflects a distinct theoretical pathway identified in prior research on park inequities. Socioeconomic vulnerability captures material and financial constraints that influence reliance on local parks for recreation [8,26]. Household composition vulnerability encompasses age structure, caregiving responsibilities, and disability, factors linked to reduced mobility and leisure opportunities [20]. Minority and language vulnerability relate to social exclusion, perceived

safety, and cultural relevance of public spaces [22]. Finally, housing and transportation vulnerability represent structural constraints within the built environment, including car dependence and weak transit connectivity, which restrict access to green amenities [12]. By linking the selected indicators to the established concepts, this study ensures that methodological choices are explicitly informed by prior scholarship and consistent with environmental justice theory (Figure 1).

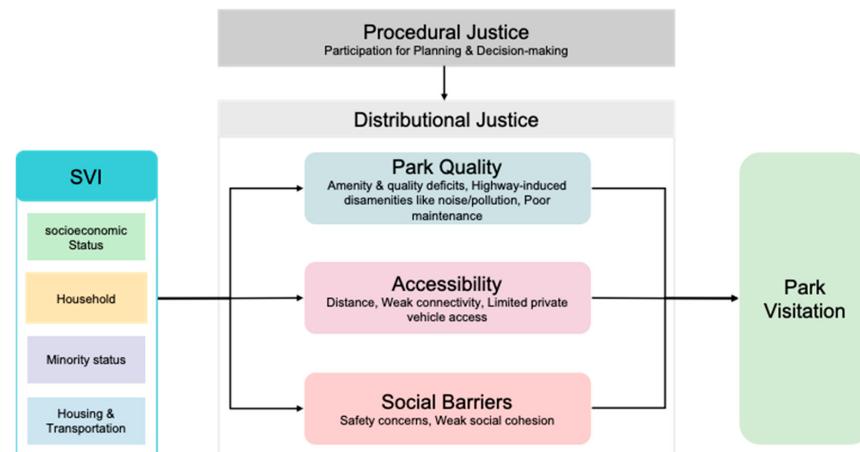


Figure 1. Conceptual Framework: Barriers Linking Social Vulnerability and Park Visitation.

From a social justice perspective, these disparities could also be interpreted as outcomes of unequal planning processes. Procedural justice emphasizes who participates in the planning processes that shape these spatial outcomes. Vulnerable communities are often excluded from participatory processes that determine where and how parks, roads, and other infrastructures are developed [12,28]. Distributional justice concerns how environmental benefits and burdens, such as parks, are unequally distributed across neighborhoods.

While social vulnerability has been shown to limit park use, such vulnerabilities are not merely individual characteristics but structural outcomes of planning decisions. For example, studies on historical redlining have demonstrated that residents of formerly redlined neighborhoods continue to face heightened social vulnerability and reduced environmental quality, decades after the original plans were enacted [18]. Extending this logic, highway segregation, a plan-driven form of spatial exclusion, may likewise exacerbate the disadvantages faced by vulnerable populations by reinforcing amenity deficits, mobility constraints, and social barriers.

In particular, the construction of highways such as Austin's I-35 exemplifies a good case of distributive injustice: large-scale mobility projects prioritized vehicular efficiency over neighborhood cohesion, dividing communities and producing long-term barriers to park access. Since the I-35 was planned in the 1950s, this research will focus mainly on the consequences of distributive justice, namely park access and visitation. The relationship between social vulnerability and park visitation, when interpreted through distributional justice lenses, is an outcome of historical planning decisions and contemporary structural exclusion.

3. Method

3.1. Study Location

Austin, the capital of Texas, is located in the south-central region of the state along the Colorado River. As of 2024, the city's population is estimated to be approximately one million [29]. Its rapid growth has been accompanied by pronounced socioeconomic disparities. In 2022, Texas reported a Gini coefficient of 0.476, reflecting significant income inequality [30]. A cross-city highway, I-35, was planned in the 1950s (Figure 2), which

boosts the city's economy. This highway is also regarded as a symbol of urban segregation (Figure 3), separating wealthier, predominantly White neighborhoods to the west from lower-income, marginalized communities to the east [31]. The population is 604,155 to the west (left) of I-35 and 552,673 to the east (right). The Supplementary Figure S1 compares the average SVI domain scores between areas west (yellow) and east (blue) of I-35 across four domains: (1) socioeconomic status, (2) household composition and disability, (3) minority status and language, and (4) housing and transportation. The bar chart highlights consistent disparities, with East Austin exhibiting higher vulnerability in all domains, particularly in socioeconomic status (0.640) and housing and transportation (0.680), indicating a spatial concentration of social vulnerability east of the highway.

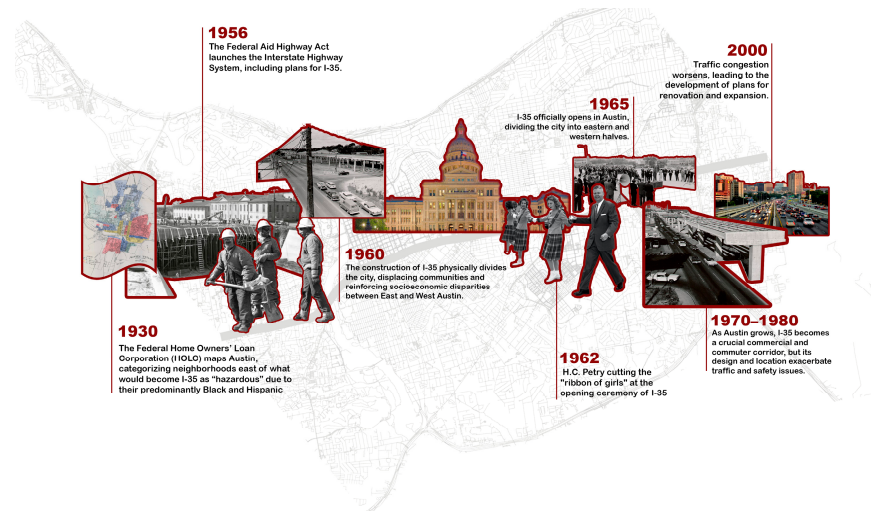


Figure 2. The context of Highway I-35, created by the author.

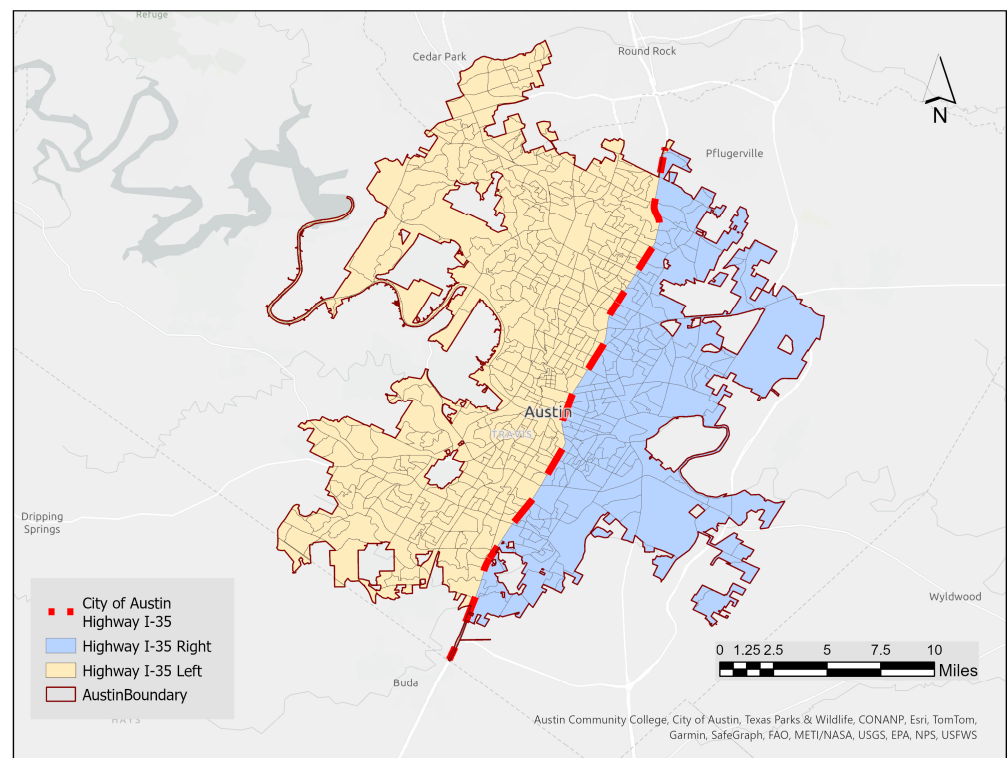


Figure 3. The Highway I-35 is a symbol of urban segregation in the City of Austin.

3.2. Data Collection and Processing

The data for this research included four parts: (1) residents' home block group and Social Vulnerability Index (SVI), (2) park features and facilities, (3) residents' park visitation and mobility information, and (4) weather data.

3.2.1. Visitors' Home Block Group and SVI

Visitor home block groups' socioeconomic and demographic characteristics were derived from the 2019 Census data. These variables included the proportion of individuals under the poverty line (undpovty), the proportion of married residents (married), population density (population_density), the total number of POI visitors (total_poi_visitors), and standardized annual household income (annual_income).

SVI refers to the degree of vulnerability of communities based on socioeconomic and demographic factors, designed to identify areas that may be more susceptible to the adverse outcomes of emergencies. Recently, it has been used as a proxy to represent various marginalized communities in social science. We employed the methodology established by the Centers for Disease Control (CDC)'s SVI, which assesses each geographic unit's social vulnerability based on 15 U.S. Census indicators. These indicators are categorized into four themes in Figure 4: (1) socioeconomic status, (2) household composition, (3) minority status and language, and (4) housing and transportation characteristics. We utilized FindSVI in R to calculate the 2019 SVI [32]. For each theme, a percentile rank is assigned based on the aggregate of its component variables, yielding a score between 0 and 1, where higher values reflect greater social vulnerability. These theme-specific scores are then added together to generate an overall SVI [33]. In this study, we used four SVI themes to measure each block group's social vulnerability to highlight each theme's effects.

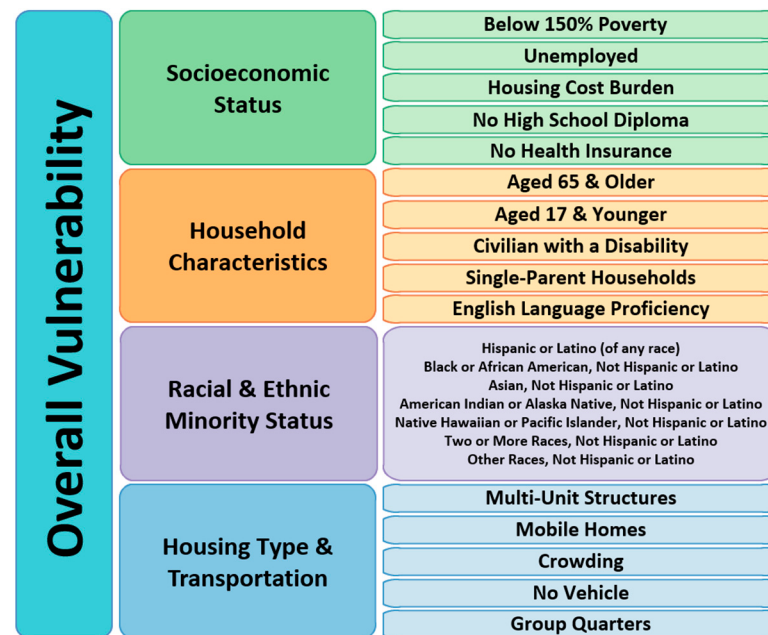


Figure 4. CDC SVI variables and themes [33]. Source: the Centers for Disease Control and Prevention and the Agency for Toxic Substances and Disease Registry. The use of this image does not imply endorsement by CDC and ATSDR of the author team. This image is available on <https://www.atsdr.cdc.gov/place-health/php/svi/index.html> (accessed on 12 September 2025), for no charge.

3.2.2. Park Features and Facilities

We used Point of Interest (POI) data for park features and facilities, which include each park's name, address, latitude and longitude coordinates, and POI category. City of

Austin classifies parks into ten types: Neighborhood, Nature Preserve, School, District, Pocket, Greenbelt, Special, Planting Strips/Triangles, Cemetery, and Golf Course. Sketch-style illustrations and key characteristics of each park type are summarized in Table 1 to provide a visual and functional overview of Austin’s park classification system. For example, greenbelts are linear parks that often follow natural features like rivers or creeks, providing corridors for wildlife and trails for hiking and biking. District parks are regional-scale parks that offer both indoor and outdoor recreational facilities and support natural resource-based activities for surrounding neighborhoods. This study focuses on parks that residents use daily. Park facility data were collected from the City of Austin’s Parks and Recreation Department website and verified using Google Maps and Google Street View. The facilities included in the analysis are: bench and table, picnic table and area, golf, soccer, skateboard, memorial, gym, shade area facility, restroom, volleyball, swimming pool, tennis, playground, baseball, scenic overlook, recreation center, basketball, and nature garden center or planting bed. Supplementary Figure S2 illustrates the spatial distribution and classification of parks within the Austin city boundary, overlaid with the division created by the I-35 highway. Different park types, Neighborhood Parks, District Parks, Pocket Parks, Greenbelt Parks, School Parks, and Nature Preserve Parks, are delineated with distinct colors to show their geographic boundaries and distribution across the city.

Table 1. Summary of Park Types in the City of Austin.

Park Type	Function	Typical Size	Service Area	Typical Features	Image
Neighborhood Park	Local recreation, daily use close to home	2–30 acres	1 mile	Playgrounds, courts, picnic tables, trails	
Nature Preserve	Preserve natural areas, support passive recreation	Varies	City-wide	Trails, signage, and native landscape	
School Park	Shared use with schools; focus on student recreation	Smaller than neighborhood parks	1 mile	Playgrounds, courts (student use prioritized)	

Table 1. Cont.

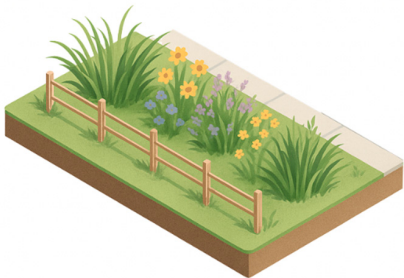
Park Type	Function	Typical Size	Service Area	Typical Features	Image
District Park	Regional recreation includes major facilities	31–200 acres	2 miles	Recreation centers, pools, sports fields, trails.	
Pocket Park	Small-scale recreation in dense areas	≤1.99 acres	¼ mile	Playground, splash pad, pavilion, benches	
Greenbelt	Linear parks for trails, connectivity, and conservation	≥50' width (200' preferred)	Varies	Trails, picnic areas, signage, and nature access	
Special Park	Unique use or feature; varies by site (e.g., museum, garden)	Varies	Varies (often city-wide)	Site-specific features (e.g., museums, art spaces)	
Planting Strips/Triangles	Beautification of road medians/intersections	<1 acre	Minimal	Ornamental plantings, signage, and aesthetic only	

Table 1. *Cont.*

Park Type	Function	Typical Size	Service Area	Typical Features	Image
Cemetery	Cultural/historic reflection space with limited recreation	Varies	Limited/local	Monuments, quiet paths, trees	
Golf Course	Recreational golf, city-wide facility	Large (varies)	City-wide	Greens, clubhouses, and parking	

Images in Table 1 were generated using ChatGPT (GPT-5.1, image-generation tool) and subsequently refined by the author in Adobe Photoshop 2024 for clarity and stylistic consistency.

3.2.3. Park Visitation and Mobility Data

This study analyzes park visitation patterns for a total of 167 parks with 723,288 visit observations, using anonymized location-based data provided by SafeGraph and Advan. Both data providers implement a range of accuracy-focused methodologies to ensure high-quality datasets. These include metrics such as the Coverage Rate and Real Open Rate, which help assess the completeness and reliability of U.S. POI datasets [34]. To validate and calibrate their data, SafeGraph and Advan referenced multiple truth sets, including government sources and industry benchmarks like Google [35]. Additionally, SafeGraph employs multiple strategies to protect user privacy, including data anonymization and aggregation, robust security measures, and strict adherence to privacy regulations [36].

A core outcome in our analysis is park visitation, which SafeGraph mobility data can directly capture at scale. These behavioral measures allow us to examine how visitation patterns vary across block groups and over time. While survey methods could capture household-level characteristics, they would be far less efficient for tracking citywide visitation dynamics. Thus, mobility data are an appropriate and necessary source for addressing our research question. We also note that our approach follows established precedents. SafeGraph mobility data can be directly linked with census tract-level SVI to examine inequities in park visitation during the COVID-19 pandemic [37]. Together, these studies demonstrate that mobility data can be reliably integrated with census-based vulnerability indicators, particularly for analyzing patterns of park visitation, which is central to our research question. Furthermore, SafeGraph's representativeness across geographic scales shows strong correspondence with census populations and only minor demographic biases [38]. Regarding ethical considerations, mobility and foot-traffic data are obtained through privacy-compliant methods that do not include any personally identifiable information; instead, they record aggregated counts of devices visiting defined points of interest.

Data providers apply multiple safeguards, including data aggregation, differential privacy adjustments, and adherence to U.S. privacy regulations such as the California Consumer Privacy Act (CCPA) [39,40].

This dataset offered information on spatial and attribute-level characteristics relevant to park visitation. Spatial-specific variables include latitude and longitude coordinates for both the park and the visitor's block group, as well as the Euclidean distance between the two points (*dist_Euclidean_km*). Park amenity variables capture the presence of benches and tables (*bench_and_table*), water features (*Presence_of_Water*), shaded areas (*shade_area_facility*), and overall park activity counts (*total_activity*). The analysis was conducted at the census block group level, which has been widely adopted in previous mobility and equity studies as an appropriate spatial unit for capturing fine-scale human activity patterns [41,42]. In total, 238,136 sampled records were analyzed in this study.

To account for weekly fluctuations in device sampling rates, the number of visits from each visitor block group to the POI was adjusted using a correction factor, as described in Equation (1). This adjustment ensures that visit counts reflect true visitation patterns despite sampling variability over time. Additionally, to accurately identify actual visits to POIs, device data were clustered based on dwell time and spatial proximity to established POI boundaries.

$$\hat{V}_{bpw} = R_{bpw} \times \left(\frac{Pop_b}{D_{bw}} \right) \quad (1)$$

In Equation (1), $\hat{V}_{bpw}$ represents the adjusted number of visits from block group b to POI p during week w . R_{bpw} denotes the raw visit count from block group b to POI p in week w , as recorded by SafeGraph. Pop_b is the total population of block group b , and D_{bw} indicates the number of sampled devices in that group during the same week. The ratio is used to correct for potential sampling bias.

$$V_{Pkt} = \sum_{i=1}^n \hat{V}_{BGikt} \quad (2)$$

In Equation (2), the total number of visits to POI k during week t , denoted as V_{Pkt} , is calculated by summing all estimated visits $\hat{V}_{BGikt}$ from block groups $i = 1$ to n , where n is the total number of contributing block groups with recorded visits in that week.

3.2.4. Weather Data

Additionally, weather data, specifically the Heat Index measured in degrees Fahrenheit, was incorporated. Heat Index reflects the perceived temperature by factoring in both air temperature and relative humidity, offering insight into thermal comfort and potential heat-related health risks. This weather data was aggregated and joined with the SafeGraph mobility dataset to enable an integrated analysis of park visitation behavior.

3.3. Data Description

Table 2 describes basic information for dependent and independent variables. The dependent variable is *real_visitor_from_BG_the_day*, defined as the ratio of park visitors from each census block group to the total population of that block group. This variable captures the relative intensity of park usage.

Independent variables captured characteristics at both the block group and park levels. Block group attributes include social vulnerability metrics (Socioeconomic Status, Household Composition, Minority Status and Language, Housing and Transportation), demographic indicators (Annual Income, Population Density, Marriage Rate, Poverty Rate), and spatial characteristics (Euclidean Distance to Park and I-35 East/West Division). Park-level variables describe physical and recreational features such as total park area, number of benches and tables, number of available activity types, presence of water bodies, average

canopy coverage, and availability of shaded facilities. Environmental conditions are also considered, including the Heat Index to account for thermal comfort. All independent variables were standardized (z-score transformation) prior to regression analysis. This standardization allows for direct comparison of coefficients across variables measured on different scales and units. Accordingly, we omit “standardized” in the table notation for clarity.

Table 2. Description of statistics of variables.

	Unit	Description	Mean	SD	Min	Max
socioeconomic_status	Index (0–1)	Composite index measuring socioeconomic conditions (higher values indicate greater advantage).	0.42	0.28	0	0.98
household_composition_disability	Index (0–1)	Composite index capturing household composition and disability status.	0.28	0.26	0.01	0.9
minority_status_language	Index (0–1)	Percentage of minority population and those with limited English proficiency.	0.45	0.22	0.02	0.83
housing_transportation	Index (0–1)	Composite index of housing conditions and transportation accessibility.	0.57	0.28	0	1
i_35	Binary (0 = West, 1 = East)	Whether the area is located east or west of Interstate 35 (Austin-specific urban division).	0.32	0.47	0	1
dist_Euclidean_km	Kilometers (km)	Euclidean distance from home BG to the park.	6.25	5.21	0.09	20
undpovty	Percentage (%)	Proportion of individuals under the poverty line.	1.96	2.18	0	13.21
married	Percentage (%)	Percentage of married individuals in the population.	41.79	18.21	0	97.79
population_density	1000 People per square km	Population density of the area.	2.05	1.64	0.03	11.08
total_poi_visitors	Count	Total number of visits to points of interest (POIs).	2337.39	2069.02	5.4	11157.17
annual_income	US Dollars (\$)	Average annual household income.	80,080.12	38,773.62	17,656.00	250,001.00
Heat Index	Heat Index (°F)	The Heat Index represents how hot it feels when relative humidity is factored in with the actual air temperature. It provides a better understanding of perceived heat and potential health risks from heat exposure.	83.33	17.51	34.01	108.44
bench_and_table	Count	Number of benches and tables available in parks.	2.73	3.93	0	16
Presence_of_Water	Binary (0 = No, 1 = Yes)	Whether a park has water features (e.g., lakes, fountains, ponds).	0.46	0.5	0	1
Canopy_MEAN	Proportion (0–1)	Average tree canopy coverage in parks.	0.45	0.28	0	0.93
Shade_area_facility	Binary (0 = No, 1 = Yes)	Whether the park has shaded areas or shade structures.	0.28	0.45	0	1
Total_sports	Count	Total number of sport types available in the park.	1.67	5.06	0	36
Parking_lot	Binary (0 = No, 1 = Yes)	Whether the park has a parking lot.	0.59	1.01	0	4

Supplementary Figure S3 displays side-by-side boxplots comparing five key indicators between the western (yellow) and eastern (blue) sides of I-35: (1) poverty rate (%), (2) married population (%), (3) annual income (USD), (4) population density (people per km²), and (5) total Point-of-Interest (POI) visitors (count). The boxplots highlight clear socioeconomic disparities, with East Austin exhibiting higher poverty and population density but lower income levels than the West. Supplementary Figure S4 presents three

thematic maps illustrating key demographic and socioeconomic patterns across census block groups, including (1) average annual household income, (2) percentage of population under the poverty line, and (3) population density. The maps reveal clear spatial disparities, with higher incomes concentrated west of I-35 and higher poverty and population density levels predominating to the east.

To evaluate the representativeness of the SafeGraph panel, we calculated block-group-level sampling rates (number of devices residing/population). Across Austin, coverage was complete (554/554 CBGs represented), with no block group falling below the minimum privacy threshold of 5 devices. The median sampling rate was approximately 5% of the City of Austin's total population (Figure 5).

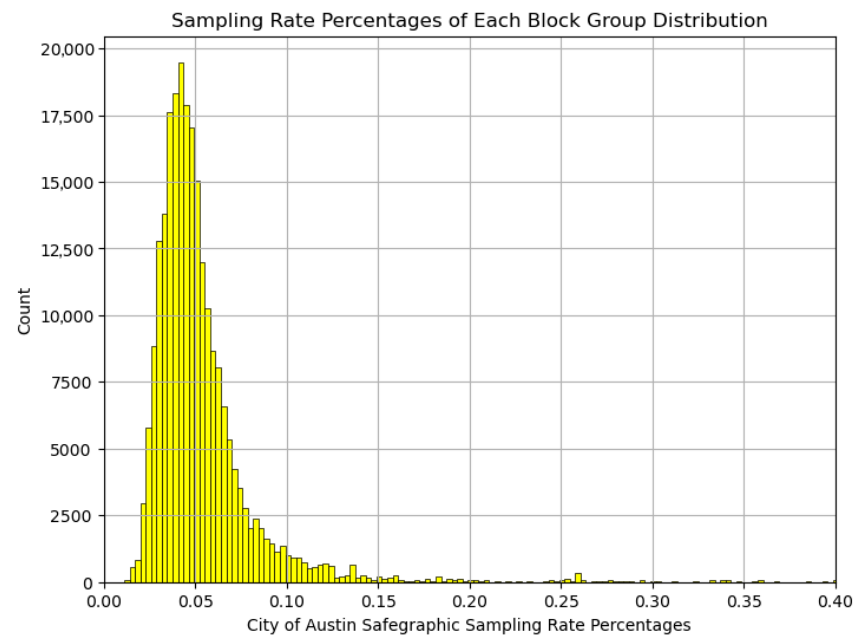


Figure 5. Distribution of SafeGraph Sampling Rates Across Census Block Groups in Austin, TX.

3.4. Statistical Modeling

Table 3 reports the OLS regression results using each block group's weighted visitation measure as the dependent variable, where visitation rates were adjusted by block group population to avoid biases caused by differing population sizes.

Table 3. OLS Regression Results: Effect of Total Population on Weekly Visitor Counts.

OLS Regression Results					
Dep. Variable:			real_visitor_from_BG_the_day		
R-squared:			0.062		
Model:			OLS		
No. Observations:			554		
Variable	Coefficient	Std. Error	t-Statistic	p-value	95% Confidence Interval
constant	1904.0249	129.922	14.655	0	1648.823, 2159.227
sum_topop	301.9364	50.05	6.033	0	203.625, 400.248

Fixed-effects models are particularly appropriate for longitudinal mobility data because they control unobserved, time-invariant characteristics of both parks and neighborhoods, yielding clearer estimates of how social vulnerability and spatial barriers influence

visitation patterns. This approach reduces bias from stable contextual differences across spatial units and isolates within-unit temporal changes, making it especially suitable for evaluating behavioral variation over time [43,44]. A fixed-effects regression model is applied to examine the relationship between social vulnerability, highway segregation, and weighted visitation. SafeGraph data are longitudinal, and the sampling in this research happened throughout the year 2019. Thus, we used fixed-effect regressions to control for unobserved heterogeneity by accounting for both time-specific and park-type-specific effects. It allowed for a more accurate estimation of the influence of social and environmental factors on park visitation over time.

The fixed-effects model is specified as follows in Equation (3):

$$RV_{b,t,k} = \alpha + \beta \cdot SVI_b + \delta \cdot I35_k + \lambda \cdot (SVI_b \times I35_k) + \gamma_1 \cdot X_b + \gamma_2 \cdot Z_k + \theta_t + \theta_{type} + \varepsilon_{b,t,k} \quad (3)$$

The fixed-effects model is advantageous for mitigating bias arising from unobserved, time-invariant factors associated with specific parks or periods. Previous research employed this approach to isolate the associations of park characteristics and temporal variation when analyzing visitation across different types of parks [35]. In Equation (3), $RV_{b,t,k}$ represents the weighted weekly number of visits from block group b to park k during week t . The variable SVI_b included a set of standardized SVI measures for block group b , comprising four dimensions: socioeconomic status, minority status and language, housing and transportation, and household composition. $I35_k$ is a binary indicator of whether park k is located east (1) or west (0) of I-35, a long-standing spatial divide in Austin. The interaction term $SVI_b \times I35_k$ captures how the associations of social vulnerability vary depending on a park's location relative to I-35. Control variables grouped under X_b include physical factors at the block group or park level, such as Euclidean distance to parks, presence of parking lots, and availability of shaded areas, benches, water features, and overall park activity. The model includes fixed effects for calendar month and park type to account for seasonal variation and structural differences among park categories. Incorporating these fixed effects led to a modest improvement in model fit, with the R^2 increasing from 0.090 to 0.094, suggesting that these temporal and categorical controls help explain additional variance in park visitation.

To assess potential multicollinearity among predictors, we calculated variance inflation factors (VIF). Most predictors had VIF values between 1 and 3, indicating very low collinearity. The two highest values were socioeconomic status (VIF = 5.62) and minority status and language (VIF = 4.39), both below the conventional threshold of 10 and only slightly above the conservative cutoff of 5. We therefore conclude that multicollinearity is not a major issue in our models.

4. Results

4.1. Distribution of Park Resources

To evaluate the spatial equity of park resources in Austin, the city was divided into two regions based on Interstate 35 (I-35). Park distribution was measured in parks per 1000 K residents, using population figures of 604,155 west (left) and 552,673 east (right) of I-35. This normalization allows for an equitable comparison regardless of population size.

As shown in Figure 6, neighborhood parks stand out as the most abundant type across both regions, with the west side featuring 38.07 parks per 1000 K residents and the east side at 23.52. Greenbelt parks also show a notable difference, with the west side offering more than double the provision (11.59 vs. 5.43). A similar disparity exists for district parks (3.31 vs. 1.81). Conversely, some park types like pocket parks and nature preserves exhibit more balance; pocket parks are nearly equal (4.97 west, 5.43 east), and nature preserves

are slightly higher in the east (3.62 vs. 3.31). School parks are relatively well distributed as well, though still slightly higher in the west (11.59 vs. 9.05).

Parks per 1000K Residents by Type and I-35 Location in Austin, TX

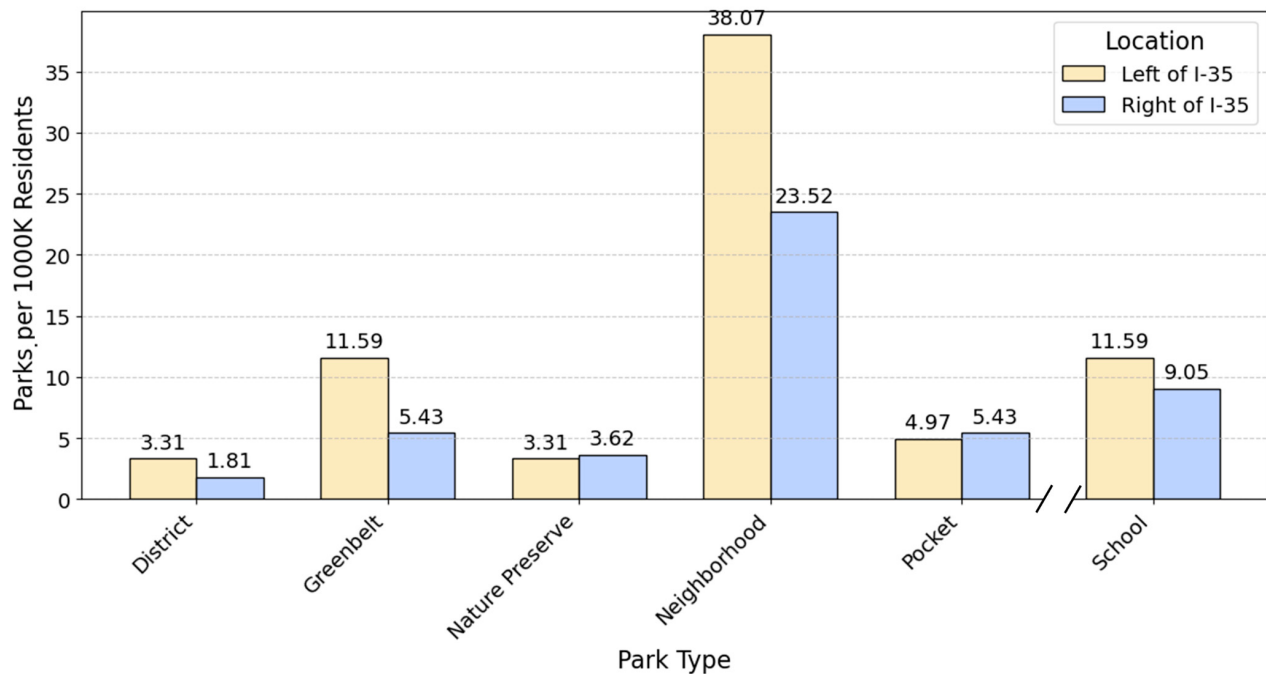


Figure 6. Distribution of Park Types by Location Relative to I-35 in Austin, TX.

As shown in Figure 7, park facilities are generally more abundant west of I-35, reflecting a clear spatial imbalance in recreational resources. Playgrounds show the greatest disparity, with 41.38 facilities per 1000 K residents on the west side versus just 19.90 on the east. Similar patterns are observed in picnic tables and area (21.52 vs. 12.67), memorials (23.17 vs. 7.24), and shade area facilities (19.86 vs. 14.48). Scenic overlooks (9.93 vs. 3.62) and basketball courts (16.55 vs. 9.05) also favor the west.

Park Facility Availability per 1000K Residents by I-35 Location in Austin, TX

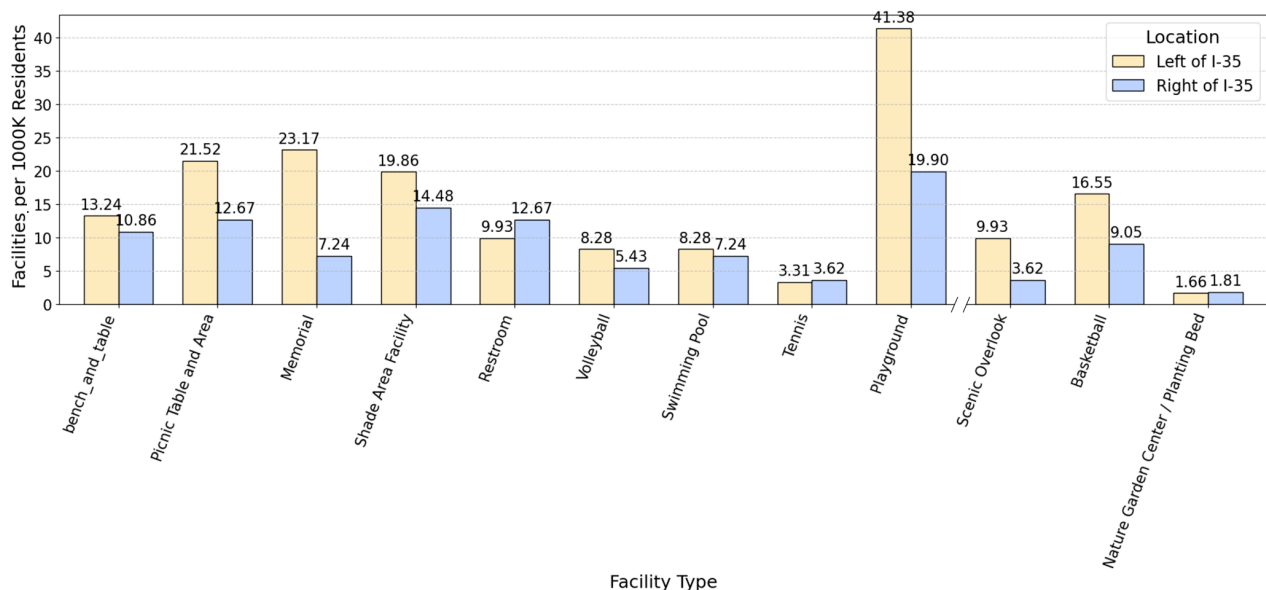


Figure 7. Park Facility Availability by Location Relative to I-35.

Some facilities show relatively balanced distributions, including restrooms (9.93 west vs. 12.67 east), tennis courts (3.31 west vs. 3.62 east), and nature garden centers/planting beds (1.66 west vs. 1.81 east).

4.2. Fixed-Effect Regression

Table 4 presents the results of a fixed-effects panel regression examining how social vulnerability relates to park visitation and whether the I-35 divide is associated with differences in these effects. The dependent variable is the weighted number of visitations from aggregated smartphone mobility at the block-group level. Key predictors are the four standardized CDC-SVI themes: (1) socioeconomic status, (2) minority status and language, (3) housing and transportation, and (4) household composition and disability. Estimation used PanelOLS (linearmodels) with diagnostics via statsmodels. To assess multicollinearity, we computed Variance Inflation Factors; all VIFs are <10, indicating no material multicollinearity concerns (see Supplementary Table S1. Variance Inflation Factor (VIF) Results for Independent Variables in the Fixed-Effects Model.

Table 4. Regression Coefficients of Models Using Different SVI Dimension: Modeling Visitor Counts.

	Model 1 Socioeconomic		Model 2 Household Composition		Model 3 Minority		Model 4 Housing and Transportation	
	Estimate	T Value	Estimate	T Value	Estimate	T Value	Estimate	T Value
Each SVI Theme	3.42 ***	34.27	−1.58 ***	−15.33	−4.82 ***	−49.07	5.68 ***	75.66
i_35	−3.95 ***	−17.68	−1.96 ***	−10.65	7.22 ***	29.21	−8.38 ***	−49.72
Interaction: Each SVI Theme × i_35	−5.43 ***	−27.74	−2.97 ***	−19.48	−8.17 ***	−38.51	1.44 ***	8.60
dist_Euclidean_km	−13.21 ***	−198.83	−12.83 ***	−193.20	−13.07 ***	−197.71	−12.60 ***	−190.82
undpovty	−4.89 ***	−63.38	−3.86 ***	−50.41	−3.16 ***	−41.40	−4.94 ***	−65.75
married	−3.10 ***	−32.37	−2.51 ***	−25.85	−1.89 ***	−19.59	−2.82 ***	−29.70
population_density	3.28 ***	48.39	3.07 ***	45.36	3.38 ***	50.81	2.98 ***	43.98
total_poi_visitors	4.69 ***	63.59	4.75 ***	64.46	4.79 ***	65.16	4.54 ***	61.80
annual_income>	1.70 ***	15.66	0.13	1.24	−1.33 ***	−12.11	2.19 ***	20.70
Heat Index	−0.46 ***	−4.24	−0.46 ***	−4.25	−0.46 ***	−4.26	−0.46 ***	−4.27
Residential_Landuse	0.81 ***	9.57	1.07 ***	12.60	1.04 ***	12.32	0.58 ***	6.88
bench_and_table	−0.24 **	−2.90	−0.29 ***	−3.50	−0.29 ***	−3.51	−0.11	−1.36
Presence_of_Water_	1.13 ***	14.68	1.44 ***	18.82	1.49 ***	19.52	0.80 ***	10.52
canopy_MEAN	−1.82 ***	−18.27	−2.39 ***	−24.14	−2.69 ***	−27.21	−1.59 ***	−16.04
shade_area_facility	−1.21 ***	−13.56	−1.05 ***	−11.84	−0.88 ***	−9.93	−1.38 ***	−15.51
Sport facility	1.55 ***	17.31	1.28 ***	14.32	1.27 ***	14.21	1.60 ***	17.99
R ²	0.097		0.106		0.10		0.09	
Fixed-Effect	Yes		Yes		Yes		Yes	

** $p < 0.01$, *** $p < 0.001$.

To capture theoretically grounded drivers of visitation while limiting omitted-variable bias, we model two construct sets. First, because socio-demographic conditions are proximate determinants of park-use propensity—and preferences and constraints vary systematically across populations—we include poverty, marital status, population density, and median income, and incorporate the four CDC-SVI themes to represent behavioral heterogeneity [45]. Second, to operationalize the characteristics of the good that users value,

we include park facilities and physical attributes consistent with Lancaster’s characteristics theory and prior evidence: seating/picnic opportunities, water features, average canopy cover, constructed shade, and sports infrastructure, which jointly influence comfort, microclimate, and activity options that shape recreation choices and intensity [46,47]. We add park-type fixed-effects to mitigate unobserved, type-specific heterogeneity [48,49] and monthly fixed-effects to absorb temperature and seasonality, reflecting well-documented weather influences on park use [50,51]. This fixed-effects specification helps control for unobserved, time-invariant differences—such as park size, geographic location, and persistent neighborhood characteristics—thereby reducing bias and improving identification [52,53].

To capture spatial context, a binary variable ($I35_k$) indicates whether a park is located east (1) or west (0) of I-35. Interaction terms ($SVI_b \times I35_k$) were included to test whether the influence of social vulnerability varies by park location relative to the I-35 divide. The model also controls for a range of block group-level demographic and contextual variables (X_b), as well as park-specific characteristics (Z_k), such as park type and size. Fixed-effects for time (monthly) and park type were included to account for unobserved heterogeneity and temporal variation. This modeling approach allows for a nuanced understanding of how different dimensions of social vulnerability influence park usage and whether these effects are unevenly distributed across the city’s east-west spatial divide.

Regression results in Table 4 showed that the I-35 differentiates how social vulnerability translates into park visitation ($\beta = -3.95$), consistent with its role as a socio-spatial segregation barrier rather than a geographic boundary. This effect is weaker on the East side of I-35, as shown by the significant negative interaction with the I-35 divide (interaction $\beta = -5.43$). Also, our results indicate that household composition and disability vulnerability are negatively associated with park visitation ($\beta = -1.58$), suggesting that areas with higher proportions of seniors, children, and individuals with disabilities tend to visit parks less often. This negative effect is amplified in East Austin, as evidenced by the additional negative interaction term (interaction $\beta = -2.97$), indicating that structural and mobility constraints further limit park use among households with caregiving duties or mobility impairments. In terms of minority status and language vulnerability, regression findings show a negative association with park visitation ($\beta = -4.82$), meaning communities with higher concentrations of minority and limited-English-speaking populations visit parks less. Negative association of minority vulnerability intensifies on the east side (interaction $\beta = -8.17$), reflecting how segregated urban infrastructure reinforces social exclusion and limits equitable park use. Lastly, housing and transportation vulnerability is positively associated with park visitation ($\beta = 5.68$), suggesting that communities with more limited housing and transportation resources are more likely to use parks. Although overall visitation is significantly lower in East Austin ($\beta = -8.38$), the positive interaction ($\beta = 1.44$) suggests a slightly stronger association between housing-transportation vulnerability and park visitation slightly strengthens on the east side, potentially reflecting necessity-driven reliance on nearby parks under constrained mobility options.

Regression comparisons reveal that the relationship between social vulnerability and park visitation differs across the I-35. Socioeconomic vulnerability increases visitation on the west side (+3.42) but reverses to a decrease on the east (−2.01), indicating a 1.6-fold reversal in direction and strength. Household composition and disability vulnerability reduce visitation in both areas (−1.58 west, −4.55 east), showing a three-fold stronger negative association on the east side. Minority vulnerability likewise shows a steeper decline (−4.82 west vs. −12.99 east), about 2.7 times stronger in East Austin. In contrast, housing–transportation vulnerability increases visitation on both sides (+5.68 west vs. +7.12 east), reflecting a slightly stronger association under constrained mobility conditions.

For control variables, the standardized coefficients show that population density, residential land proportion, presence of water features, and total park activities are positively associated with weighted park visitation. In contrast, distance to parks, poverty rate, marriage rate, heat index, canopy coverage, shaded area facilities, and the number of benches and tables are negatively associated with weighted park visitation. Annual income and the I-35 variable show mixed directions across different weighted park visitation, reflecting complex spatial and socioeconomic interactions.

Although several predictors were significant, the model explained a modest share of variance ($R^2 \approx 0.09$). This aligns with prior mobility studies, where behavioral randomness and contextual diversity limit predictive power [54,55]. Because fixed-effects models capture only within-unit changes, the low R^2 reflects the complex nature of visitation behavior rather than weak relationships.

5. Discussion

5.1. Findings

This study examined how social vulnerability and highway segregation, particularly in relation to Austin's I-35, shape patterns of park visitation. Using a longitudinal dataset, combined with park facility data and census tract-level social vulnerability metrics, the study conducted fixed-effects modeling to assess how park use is influenced by both place-based disparities and demographic characteristics.

Results reveal that the effects of social vulnerability on park visitation vary by dimension. Socioeconomic and housing–transportation vulnerabilities increase visitation, likely reflecting reliance on nearby parks, whereas household and minority vulnerabilities reduce visitation. Prior demographic studies and regional planning records indicate that areas east of I-35 contain higher concentrations of socially vulnerable residents and fewer mobility and public infrastructure investments. This spatial context explains why some vulnerability effects appear stronger on the east side, reflecting existing inequities that the corridor reinforces rather than new disparities it creates. The highway further widens these disparities by reinforcing access barriers for vulnerable communities, showing that segregation infrastructure amplifies or suppresses vulnerability effects rather than creating disparities on its own.

These findings align with prior research on green-space equity and environmental justice, which emphasizes that unequal park use often reflects structural constraints rather than individual choice. Low-income and mobility-limited residents frequently engage in “necessity-driven visitation,” using nearby parks despite infrastructural or environmental barriers. Prior studies also highlight that perceptions of safety, time availability, and social inclusion shape park engagement, particularly among elderly, single-parent, and limited-English households [20,22]. Consistent with broader evidence from U.S. cities, our results support the view that urban segregation systematically constrains equitable access to green space and reduces park-based activity [25,55].

While East Austin already exhibits higher social vulnerability and lower infrastructure investment, the findings indicate that the I-35 operates as an amplifying mechanism that reinforces these disparities. Parks in East Austin are generally characterized by lower maintenance quality and fewer amenities [56]. Prior studies demonstrate that well-maintained parks with diverse amenities and better infrastructure attract more frequent and longer visits, whereas poorly maintained or under-resourced parks discourage use [27]. Moreover, community engagement and local programming are critical for sustaining park use; when residents participate in park planning and activities, they develop a stronger sense of ownership and belonging, which in turn enhances visitation [57]. Collectively, these factors help explain why the highway amplifies behavioral disparities in park visitation across Austin.

Taken together, segregation interacts with social vulnerability to shape who can benefit from public green spaces, emphasizing spatial and structural processes that constrain equitable access. By framing these results within the broader concept of justice, the study highlights that disparities in park visitation represent not only spatial inequality, where infrastructural decisions have systematically marginalized certain groups from environmental benefits. The unequal distribution of green access (distributional injustice) as a consequence of the highway reinforces long-standing patterns of spatial exclusion. Viewing Austin's I-35 through this justice-oriented lens allows the findings to extend beyond a local context, underscoring broader implications for urban accessibility and park equity. In this sense, the study contributes to ongoing debates in environmental justice and urban planning, suggesting that equitable access to parks should be treated as a matter of rights and governance rather than convenience or proximity.

The mechanisms identified here, including structural barriers, constrained mobility, and necessity-driven use shaped by spatial segregation and infrastructure design, are not unique to Austin but reflect systemic processes observed in many automobile-oriented cities worldwide. Thus, addressing such inequities requires not only physical interventions, such as reconnecting fragmented park systems or mitigating highway barriers, but also procedural reforms that ensure inclusive participation and representation in urban planning. This study therefore contributes to a generalizable understanding of how spatial segregation perpetuates environmental inequity across diverse urban contexts.

5.2. Contribution

First, this research provides a theoretical contribution by quantitatively identifying how highway segregation amplifies or mitigates the effects of social vulnerability on park accessibility. While prior studies have documented that social vulnerability and segregation independently influence environmental equity, few have examined their interactive relationship. By reframing the highway as a structural moderator rather than a mere spatial boundary, the study identifies how infrastructural segregation shapes behavioral access, moving from describing disparities to explaining their underlying mechanisms.

Second, this study provides a methodological contribution by introducing a longitudinal analytical framework that captures how infrastructure and social conditions jointly linked with behavioral access to parks. Methodologically, it moves beyond proximity-based and cross-sectional approaches by using longitudinal mobility data to measure realized visitation rather than assumed access. This framework enables the identification of within-tract temporal variations and mitigates biases arising from static spatial proximity models. By linking mobility behavior with infrastructural barriers, the study demonstrates how high-frequency, real-world data can reveal dynamic patterns of access that traditional accessibility models overlook.

Finally, this study underscores the practical relevance of spatial modeling by using the results to infer potential accessibility trends and to inform data-driven interventions. The analytical framework developed here can be extended to evaluate the effectiveness of existing urban design strategies or to simulate the association of alternative planning scenarios. These applications demonstrate the broader utility of linking quantitative spatial evidence with equity-oriented policy design.

Vulnerability metrics such as the Social Vulnerability Index (SVI) have been increasingly adapted across diverse global contexts, including Europe and Asia, to assess inequalities in disaster exposure, health outcomes, and environmental accessibility [33,55]. This growing body of international applications demonstrates that vulnerability frameworks are both methodologically robust and contextually flexible, capable of reflecting local cultural, political, and institutional systems. Building on this foundation, the framework employed in this study

offers a transferable approach for comparative analyses of infrastructural segregation and park accessibility, enabling scholars and policymakers to examine how social vulnerability interacts with urban form to shape environmental equity across cities worldwide.

5.3. Implication

To translate these findings into practice, local and regional agencies could integrate equity-based accessibility metrics into their infrastructure and capital improvement planning. For instance, prioritizing pedestrian overpasses or tree-lined buffer zones near high-vulnerability tracts could directly mitigate the physical and psychological barriers identified in this study.

Building on the model results, quantitative projections provide an applied perspective on how mitigating segregation could enhance park accessibility and use. Model estimates indicate that reducing the segregation-related differences along the I-35 divide by 10% would increase park visitation in high-vulnerability tracts by approximately 6–8% (95% CI = $\pm 2\%$), whereas adding one new cross-highway connection per kilometer is projected to yield an additional 3–5% increase ($\pm 1.5\%$) in visitation. To aid interpretation, coefficients were converted into approximate effect sizes for a representative census block group (CBG). Assuming an average of 50 visits per 10,000 residents, a one-standard-deviation rise in socioeconomic vulnerability ($\beta = 3.42$) corresponds to roughly 3–4 more visits per 10,000 residents in West Austin. On the east side, where the interaction effect ($\beta = -5.43$) dominates, visitation declines by about 2 visits per 10,000 residents, resulting in an overall contrast of approximately 5–6 visits per 10,000 residents between the two sides of the I-35 divide.

These findings carry broader implications for equitable urban planning. They emphasize the need to view infrastructure not only as a physical system but also as a social determinant of accessibility and well-being. Planning strategies that reconnect divided neighborhoods, enhance cross-highway connectivity, and invest in underserved communities can transform the urban fabric from one of separation to one of inclusion. In this way, the study bridges empirical evidence with actionable insights, reinforcing the role of data-driven urban design in advancing environmental justice and spatial equity.

5.4. Limitation

However, this study had several limitations, which also offer implications for future research. First, this study is limited by the absence of key contextual variables that are likely to influence park visitation, including perceived safety, public transit accessibility, and the cultural relevance of park spaces. These factors, while difficult to quantify using secondary data sources, may significantly shape individual decisions to visit parks, particularly among socially vulnerable populations.

Also, while mobility big data offers valuable insights into visitation patterns, it does not capture qualitative dimensions of park use such as user satisfaction, perceived safety, or cultural relevance. Although our two-way fixed-effects specification accounts for unobserved heterogeneity across parks and time, it cannot capture time-varying qualitative factors such as shifts in perceived safety, programming, or community attachment.

Additionally, this study is limited by the unavailability of certain contextual and infrastructure-related variables, such as park maintenance quality, lighting conditions, nearby crime rates, and detailed network connectivity measures (e.g., transit accessibility and intersection density). Future research incorporating these dimensions could more fully disentangle the influence of environmental quality and accessibility from social vulnerability in shaping park visitation patterns.

To address these limitations, future research should incorporate contextual variables through mixed-method approaches, including community surveys, ethnographic fieldwork,

or other qualitative methods. Doing so would provide a more comprehensive understanding of how different populations experience and value park spaces. Additionally, the analysis is limited to a pre-pandemic year (2019); exploring post-pandemic changes in park visitation could reveal how COVID-19 reshaped public space usage, particularly for vulnerable communities. Reliance on data from 2019 also introduces a temporal limitation, as findings may not fully capture more recent demographic and urban changes, and caution is warranted in generalizing beyond the study period.

Moreover, limitations include potential bias in mobile data sampling, particularly underrepresentation of populations with limited smartphone access, including older adults, low-income individuals, and those less likely to share location data, and the static nature of SVI metrics, which may not fully reflect short-term demographic changes. This study focuses specifically on the urban context of Austin, Texas, and relies on U.S.-based datasets. Due to limitations in data availability and the context-specific nature of urban form, these findings may not be generalizable to other cities, particularly those in non-U.S. or compact European settings with different planning histories, mobility patterns, and social structures.

We acknowledge that indicators of vulnerability and park access may vary significantly by geographic, cultural, and political context. As such, future research should explore how alternative vulnerability frameworks, such as the multi-level European-wide composite indicator [30], could be adapted to other urban settings to assess disparities in park use and access across different international contexts.

Finally, this study uses the I-35 highway as a binary spatial boundary to represent urban segregation. While I-35 has historically symbolized the east–west divide in Austin, this approach might simplify complex intra-urban disparities; usage of a single dividing line does not capture variation in infrastructure quality, park condition, or neighborhood investment within either side of the city. Future research should consider incorporating more detailed spatial indicators, such as differences in park distribution, facility age, and built environment features along the I-35.

6. Conclusions

This study offers evidence on how highway segregation shapes and amplifies the relationship between social vulnerability and park visitation, using the case of Austin, Texas. While some vulnerable groups, particularly low-income residents, rely more heavily on parks, their actual usage is constrained by structural and spatial inequities, especially in East Austin, where the I-35 highway continues to function as a major physical and social access boundary, limiting equitable park access. The findings confirm that urban parks are not equitably used, even when they are spatially proximate. Patterns of visitation reflect deeper, layered connections, from highway segregation to an individual's socioeconomic status. Minority populations, households with mobility limitations, and residents of disadvantaged neighborhoods continue to face disproportionate barriers to accessing the benefits of urban green spaces.

The policy implications are clear: achieving green space equity requires multidimensional, justice-oriented interventions that extend beyond physical improvements. For urban planners, policymakers, and public health professionals, this research underscores the importance of integrating both distributional and procedural equity into park planning, funding, and evaluation. Realizing green equity requires coordinated action that considers not only where parks are located, but also how they are designed, connected, and experienced by the communities they serve. Cities must invest in connectivity infrastructure, inclusive programming, and participatory design while systematically directing resources toward areas of greatest social vulnerability.

Future research should complement mobility-based analyses with community surveys, interviews, and participatory mapping to better validate the behavioral representativeness of visitation patterns and capture qualitative dimensions of park use, such as satisfaction, perceived safety, and cultural relevance, particularly among digitally underrepresented populations. Additionally, future studies should investigate alternative explanatory mechanisms, examining whether disparities in park visitation arise not only from highway segregation itself but also from broader community-level segregation and neighborhood disinvestment patterns. Incorporating more detailed geographic indicators, such as park distribution, facility age, and built-environment characteristics, would further enable a more precise assessment of spatial heterogeneity in accessibility and help disentangle the structural and social factors shaping urban park equity. While this study provides consistent results across model specifications, we acknowledge that additional robustness checks—such as placebo boundary tests or bandwidth sensitivity analyses—could further validate the findings. However, such tests were not feasible due to the aggregated structure of SafeGraph mobility data and the lack of multi-year temporal variation. Finally, we suggest that future research apply spatial econometric or quasi-experimental methods (e.g., regression discontinuity design, spatial lag models) to isolate boundary-specific effects and refine causal inference.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/urbansci9120512/s1>. Figure S1: Bar chart comparison of Social Vulnerability Index (SVI) domain scores across the I-35 corridor in Austin, Texas. Figure S2. Spatial distribution of park types and division across the I-35 corridor in the City of Austin, Texas. Figure S3. Boxplot comparison of demographic and socioeconomic characteristics across the I-35 corridor in Austin, Texas. Figure S4. Spatial distribution of key demographic and socioeconomic variables across census block groups in the City of Austin, Texas. (1) Average annual household income (USD), (2) Population under the poverty line (%), and (3) Population density (people per square kilometer). Figure S5. Spatial distribution of SVI. Figure S6. Directed Acyclic Graph (DAG) of the Hypothesized Mechanisms Linking Highway Segregation, Social Vulnerability, and Park Visitation. Figure S7. Correlation Matrix Heatmap for Variables. Tables S1: Variance Inflation Factor (VIF) Results for Independent Variables in the Fixed-Effects Model. Table S2. Description of statistics of variables for West (I-35 = 0). Table S3. Description of statistics of variables for East (I-35 = 1).

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Abbreviations

The following abbreviations are used in this manuscript:

SVI Social Vulnerability Index
POI Point of Interest

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