THESIS

INFLUENCE OF TREE PLANTING GUIDELINES ON STREET TREE DISTRIBUTION ALONG BUS CORRIDORS

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ABSTRACT

INFLUENCE OF TREE PLANTING GUIDELINES ON STREET TREE DISTRIBUTION ALONG BUS CORRIDORS

As cities invest in public transportation to promote sustainable urban development, urban forestry presents an important yet underutilized opportunity to enhance commuter experience and environmental resilience, as street trees can significantly reduce urban heat island effects and enhance the comfort of bus users. This study examines how municipal tree planting regulations influence street tree density along bus routes in 15 U.S. cities. Analysis of street tree distributions revealed that in 73% of the cities, tree density was lower along bus routes compared to non-bus routes. Spacing regulations generally addressed minimum distances between trees; required setbacks from utilities; proximity to traffic control devices; distance from structures such driveways; and spacing from street corners. Using a generalized linear model and regulation severity scores, we assessed the impact of these regulations on tree density. The analysis revealed that certain requirements—such as minimum distances between trees, structures, traffic controls, and corners—were significantly associated with variations in tree density ($p < 0.0001$), however the degree of influence of the regulation on street tree density was dependent on whether the street had a bus corridor. These findings underscore the uneven influence of municipal regulations on street tree coverage and highlight the need for cities to evaluate how regulatory frameworks can support more equitable, climate-resilient transportation corridors.

ACKNOWLEDGEMENTS

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DEDICATION

I would like to dedicate this thesis to mi familia and my partner, Jacob Landsberg.

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Chapter 1

Introduction

Cities are complex, evolving systems where urban policies can help shape landscapes, infrastructure, and quality of life. Among these policies, municipal guidelines can influence the distribution of urban forests (including street trees). These trees are key assets that provide shade (Yu et al., 2020), improve air quality (Nowak et al., 2006), and mitigate urban heat (Shashua-Bar & Hoffman, 2000). Recent research shows that air temperatures decrease linearly with increasing tree cover within 10 meters, highlighting that even small additions of tree canopy can effectively cool the air and reduce heat exposure risks (Ettinger et al., 2024). However, tree planting guidelines are often inconsistent across different cities, shaped by varying priorities, spatial constraints, and governance structures (Jim et al., 2018; Lawrence et al., 2013). These inconsistencies can affect the equitable distribution of trees, particularly in transportation corridors where trees could play a critical role in improving public transit infrastructure and subsequently reducing CO_2 emissions by reducing personal vehicle usage as more people opt for the bus (Li et al., 2024). As urban areas generate almost 70% of global CO_2 emissions related to energy consumption (Seto et al., 2014) and experience elevated temperature due to the urban heat island effect (Oke, 1973) and deteriorating air quality (Singh et al., 2020), finding avenues to reduce emissions will help cities provide healthier and cleaner environments for their residents.

Public transportation plays a vital role in reducing urban carbon emissions and promoting sustainable transit. Yet, the experience of waiting for and using transit is often overlooked in transportation planning. Expanding public transit, particularly bus systems, is a key strategy for cutting CO_2 emissions, especially for low-income communities that disproportionately rely on public transit (Parker et al., 2021). A UK study found that conventionally fueled cars produce 30g CO_2/kilometer (km) per person, while conventionally fueled buses produce just 16.3g CO_2/km per person, nearly halving emissions per rider (Logan et al., 2020). While trees are not often associated with mobility, trees play a crucial role in making public transit more appealing and accessible.

Street trees enhance commuter experience by providing shade, reducing heat exposure (Armson et al., 2012), and improving overall comfort at bus stops (Lagune-Reutler et al., 2016). Lanza and Durand (2021) found that tree canopies surrounding bus stops mitigate the negative impact of high temperatures on ridership. Specifically, during warm seasons, each one-percent increase in tree canopy was associated with a 1.6% smaller decrease in ridership compared to stops without trees (Lanza & Durand, 2021). Additionally, urban greenery can improve air quality, lowering exposure to harmful pollutants for transit riders (Nowak et al., 2006). By integrating trees into transit planning, cities can encourage public transit use, reduce emissions, and create healthier urban environments. As the global urban community– already accounting for over 50% of the world population– increases, cities are adapting and mitigating climate change to secure a healthy and sustainable future (United Nations, Department of Economic and Social Affairs, Population Division, 2019). The abilities of trees to improve the urban environment and lives of residents have long been known and utilized by cities (Endreny, 2018). Many communities have looked towards trees as one solution, as they offer ways for cities to adapt to climate change, such as addressing urban heat islands. However, despite current dialogue on the importance of trees in cities, planting more trees alone will not drastically reduce the amount of CO_2 emissions from cities. Simulations from one study found that doubling the density of tree plantings would have a negligible effect on total urban CO_2 emissions, but enacting land use and transportation policies, which reduce the intensity of urban sprawl, could result in a 22% reduction in CO_2 emissions by 2030 as compared to a business-as-usual scenario (D. Pataki et al., 2009). As cities aim to decrease their carbon footprint, incorporating more trees into their urban infrastructure can be a starting point, but other projects such as encouraging public transportation would also significantly contribute to greenhouse gas emission decreases, since on average, a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide each year (U.S. Environmental Protection Agency, 2025). Trees can support this transition from private to public transportation. Studies have found that trees enhance public transportation experiences in multiple ways. For example, riders at tree-lined bus stops often perceive their wait times as shorter than they actually are, contributing to greater satisfaction with transit services (Lagune-Reutler et al., 2016). Additionally, the shade and cooling effects of trees can help mitigate health impacts of rising temperatures and heat-related stress (Lanza & Durand, 2021). Integrating trees into public transit infrastructure may encourage greater ridership and reduce reliance on personal vehicles, ultimately helping lower greenhouse gas emissions in urban areas.

Despite their potential benefits, trees are often excluded and deprioritized from transportation planning due to concerns about spatial conflicts and infrastructure compatibility (Roman et al., 2020). Current municipal guidelines may either limit tree planting near transit stops or fail to consider their role in improving public transportation. This study examined the street tree planting guidelines across 15 U.S. cities to assess how municipal policies influence urban forest distribution along streets and bus routes. By analyzing these guidelines, this research aims to identify gaps and opportunities to integrate urban forest with sustainable transportation planning, ultimately supporting access to public transit and healthier urban communities.

Chapter 2

Literature Review

2.1 Urban Forests, Street Trees and the City

Street trees form a vital subset of the urban forest. Although definitions vary, street trees are commonly described as ‘trees growing along public street right-of-way and managed by the city’, although not always under municipal jurisdictions (McPherson et al., 2016). Historically, street trees have contributed to urban aesthetics and public health. Interest in street trees and urban forestry, in general, has grown as communities grapple with growing urban populations and a growing interest in improving the urban landscape. In an attempt to manage the complexity of urban systems, urban forestry has permeated policy and legislation (Konijnendijk et al., 2006), with codes and regulations enacted, as a means of controlling both the built and natural environment. Urban forest governance falls under the greater umbrella of environmental governance, defined as instituting interventions with the goal of changing environmental-related incentives, comprehension, resolutions and conduct (Lemos & Agrawal, 2006). A survey of urban tree policies in the Greater Toronto Area revealed considerable variation in the adoption and type of municipal urban forestry policies, highlighting differences in how municipalities regulate street trees and private property (Conway & Urbani, 2007). Understanding governance and variation in governance can help to explain the physical layout of the urban forest, including the incorporation of street trees into the urban landscape as a type of urban infrastructure.

2.2 Municipal Policies and Governance

Governance frameworks influence not only decision-making processes but also the physical implementation of urban forestry initiatives. As municipalities formalize their approaches, urban and community forestry programs have expanded across the United States since the 1980s, largely influenced by federal support from the 1990 Farm Bill and subsequent versions (Hauer et al., 2008).

With this expansion, cities began developing written guidance, such as municipal tree ordinances, to manage their urban forests. One significant influence has been the Tree City USA program, established in 1976 as a collaboration between the National Arbor Day Foundation (NADF), the US Department of Agriculture (USDA) Forest Service, and the National Association of State Foresters (Rosenow & Yager, 2007). To qualify for the Tree City USA program, a municipality must : (1) establish a tree board or department; (2) form an annual community forestry program with financial provisions for trees and tree care; (3) hold an annual Arbor Day proclamation and observance; and (4) enact a public tree care ordinance (Fazio, 1990).

2.3 Urban Forestry Decision-Making and Municipal Code

These foundational policies establish a framework for municipal tree management, influencing how cities regulate planting, maintenance, and removal. Tree ordinances, in particular, shape these processes, although their legal basis and enforcement vary by municipality (Larson et al., 2020). Urban forestry differs from conventional forestry in that urban forests prioritize recreational, aesthetic, and environmental functions rather than wood production (C. C. Konijnendijk, 2000). Given their proximity to city centers, urban forests require more localized, community-driven policy processes that balance tree preservation and planting with infrastructure needs. Municipal codes and policies guide urban planners, landscape architects and city officials in managing urban trees. These decisions are often coordinated by municipal managers, who navigate multiple stakeholder interests (Ordóñez et al., 2020). Tree ordinances generally fall into two categories: those regulating trees on public property (e.g., street trees) and those governing private property (Templeton & Rouse, 2012). For street trees, cities may establish right-of-way requirements, sidewalk design standards, and guidelines for planting width, species selection, and utility clearance (Templeton & Rouse, 2012). However, these guidelines often serve as flexible frameworks rather than strict rules, leading to varied approaches across municipalities (Miller, 2007). Municipal tree ordinances commonly address several governance aspects and typically designate officials such as a city forester, urban forestry commission, or public works department to oversee tree management (Hargrave et al., 2022), (Hilbert et al., 2019). These ordinances grant authority to manage resources, set priorities, review development plans, and enforce rules. A review of municipal urban forestry management programs in the United States highlights that many communities have established tree ordinances to guide urban forestry efforts, and larger municipalities are more likely to have a formal program in place (Hargrave et al., 2022). Ordinances may include technical standards for tree care, such as pruning guidelines, species selection, planting specification, and pest or disease management. Additionally, tree ordinances can outline protections for heritage or landmark trees, specify requirements for tree removal permits, and establish penalties for unauthorized tree damage or removal (Hilbert et al., 2019). Research indicates that tree preservation ordinances can significantly influence urban canopy cover and the protection of street trees during construction (Pike et al., 2021), and municipalities with heritage tree protections had more canopy coverage than municipalities without those protections (Hilbert et al., 2019). While some cities consolidate tree regulations into a single ordinance, others distribute them across various sections of municipal codes, zoning laws, and landscape standards. Variations in these ordinances reflect differing local priorities and standards, impacting the sustainability and management of urban forests (Lavy & Hagelman, 2019). Planting guidelines within these ordinances contribute to broader urban forestry governance by balancing tree canopy goals with safety, infrastructure, and urban design considerations.

2.4 Spatial Constraints and Strategic Urban Tree Planting

However, the effectiveness of these guidelines is often constrained by the availability of suitable planting space, which varies across urban landscapes. Escobedo et al. (2010) study on subtropical U.S. cities found that public land suitable for additional trees primarily includes vacant areas and transportation corridors. In Gainesville, Florida, most available planting space was within transportation land use (4.2 km^2). However, their study also found that converting these non-treed areas into urban forests would have only a modest impact on overall CO_2 sequestration. In Gainesville, urban trees offset just 3.4% of city-wide emissions, suggesting that while urban forests contribute to carbon mitigation, their effectiveness depends on long-term management, species selection, and integration with broader climate policies (Escobedo et al., 2010). Similarly, road easements in an Australian city accounted for 7.0% of land cover and 36.7% of public green space, highlighting their importance for urban forestry expansion (Marshall et al., 2019). A study conducted in Australia found that if cities are to meet canopy cover targets, there must be changes in residential development design to allocate more space for trees in both public and private areas (Torquato et al., 2025).

Planting guidelines and municipal codes contribute to the broader governance of urban forestry by shaping the "rules of the road" for tree management. Some requirements, such as minimum planting distances from intersections or utility lines, are formally codified in municipal ordinances (Neupane et al., 2022). Yet other guidelines may exist as best practices developed by urban forestry departments but lack formalized documentation and strict enforcement mechanisms. Research analyzing vegetation ordinances in the southern United States found that while these regulations provide a foundation for managing urban forests, they often contain unclear provisions, duplications, or contradictions that limit their effectiveness (Neupane et al., 2022). Understanding how municipal codes influence tree planting can help planners optimize limited space and strategically integrate trees into public infrastructure.

2.5 Benefits of Street Trees on Public Transportation

2.5.1 Perception of Wait Time for Bus and Street Trees

Waiting for buses is a large part of commuting by public transit. The wait time and perception of wait time for buses affects the commuter's perception of service quality (Mishalani et al., 2006). Transit agencies look to improve commuter's transit experience by improving on-time arrivals at bus stops and reducing the overall wait time for passengers (Watkins et al., 2011). On average patrons feel an acceptable wait time for their bus ranges from from five to 15 minutes, although improving bus stop facilities increases the amount of tolerable wait time for bus commuters (Arhin et al., 2019). For example, when bus commuters had waits longer than five minutes, perceptible pollution and exposure to traffic led to significant overestimates of wait times, while the presence of dense, mature tree cover led commuters to significantly underestimate their wait times, an effect strong enough to compensate for the effects of both air pollution and traffic awareness (Lagune-Reutler et al., 2016). Additionally, trees have been found more effective at cooling than bus shelters ;tree-shaded areas were 3.2°C cooler than unshaded areas and that shelters provided less cooling than trees (Lanza et al., 2025).

2.5.2 Trees Encourage Active Transportation

Public transit users tend to engage in more moderate-intensity physical activity than those who rely on personal vehicles, accumulating an additional five to 10 minutes of walking per trip (Lachapelle et al., 2011). This increased physical activity results from walking to and from transit stops, as well as to nearby destinations at home and work (Del Rosario et al., 2022). By promoting pedestrian activity, cities can indirectly encourage greater transit use, reinforcing the shift away from car dependency. Street trees play a crucial role in fostering walkable environments. Studies show that tree-lined streets significantly increase walking levels, making pedestrian travel more appealing and comfortable (Vich et al., 2019). As cities look to expand public transit infrastructure and reduce reliance on personal vehicles, strategically planting trees along bus routes can enhance the pedestrian experience, thereby supporting transit use. However, despite the well-documented benefits of urban forests for both walkability and public transportation, municipal policies rarely integrate tree planting with transit planning.

Beyond walking, street trees also support multi-modal transportation by improving conditions for cyclists. In a study on cycling infrastructure preferences, participants favored pathways with trees over those without, indicating that tree-lined routes enhance both comfort and perceived safety (Lusk et al., 2020). By incorporating trees into bike lanes and transit corridors, municipalities can encourage cycling as a viable first- and last-mile connection to public transit, further strengthening sustainable transportation networks.

2.5.3 Vulnerable populations are most reliant on Public Transit

Even as cities try to address the consequences of climate change, the existing ramifications have already placed residents under dangerous conditions and will continue to exacerbate existing health conditions such as heat exposure, in particular those of marginalized identities. In the instance of urban heat, low income communities experience higher heat exposure than wealthier communities (Chakraborty et al., 2019). Being able to address the inequities in experiencing the consequences of climate change is paramount to creating healthy and sustainable urban communities for all residents. While street trees may encourage the switch for non-public transit commuters to public transit, those who are currently reliant on public transit also benefit from the increase of street tree plantings, especially as they may have no alternative means of transportation. On average, people with low incomes are more likely to use public transit for commuting (Parker et al., 2021). As low income individuals are less likely to have access to a motor vehicle, they are more dependent and affected by the conditions of the bus, bus stop and routes, along with all the health consequences of commuting by bus (Turrell et al., 2013). Additionally, individuals reliant on public transportation (disproportionately low income) will continue to use public transportation regardless of the increasingly hot environment created as a result of climate change (Lanza & Durand, 2021). Providing safe and healthy commutes for all urban dwellers is necessary to creating equitable communities.

2.5.4 Trees Reducing the Heat and Keeping Commuters Safe

Urban commuters are exposed to the urban heat island (UHI) effect, a phenomenon in which urban areas experience significantly higher temperatures than surrounding rural areas due to the concentration of heat-absorbing surfaces and reduced vegetation (Oke, 1973). Premature mortality has been linked to high ambient temperature (Guo et al., 2014), and, specifically in urban areas, UHIs can contribute to premature deaths, especially during the summer (Iungman et al., 2023). According to the Pew Research Center (2016), there is a significant racial difference between those who use urban public transit (including bus usage) with 34% of Black residents and 27% of Hispanic residents reporting taking public transit daily or weekly as compared to only 14% of White residents. Black and Hispanic urban communities more frequently rely on public transit which puts them at higher risk of exposure to extreme heat when commuting by bus. The percentages of poor and minority residents (predominantly Hispanic neighborhoods) were found to have a positive correlation with heat stress exposure than their higher-income and predominantly white neighborhoods counterparts (Harlan et al., 2006). As a way to protect residents from heat (including heat stroke, heat exhaustion and other heat related health concerns), cities can use the shade provided by trees as a means to reduce heat exposure, planting trees at bus stops and along bus routes as commuters walk to and from bus stops. Shade structures and trees were the infrastructure features identified most often as having perceived cooling benefits (Dzyuban et al., 2022). Many cities struggle with urban heat islands, and trees in urban settings are shown to reduce peak surface temperatures of concrete by up to 12°C, acting as an effective method to reduce urban heat islands (Armson et al., 2012). Shade structures and trees were the infrastructure features identified most often as having perceived cooling benefits (Dzyuban et al., 2022). One study conducted in the summer of 2018 in Phoenix, Arizona found that current infrastructure standards and material choices for bus stops in the city were insufficient to provide thermal comfort, even exposing riders to health risks. During the study, almost half of the participants felt hot or very hot at the time they were surveyed, and more than half reported being thermally uncomfortable; however, on average, the physiological equivalent temperature was reduced by 19°C in the shade. Although only 3.6% of participants were under a tree when completing the survey, trees were identified to have cooling benefits by nearly as many participants (60.2%) (Dzyuban et al., 2022).

2.6 Municipal Codes to Increase Street Trees along Bus Routes

As cities look to enhance their bus systems, urban forestry can play a pivotal role. By using the existing framework of municipal street tree policies– including spacing requirements and planting guidelines–cities can strategically update their policies to expand tree plantings along bus routes. Yet the scholarship around municipal policies for urban forestry, and street tree planting more specifically, has not been exhaustively studied. By investigating the distribution of street trees along public bus routes and stops in different large US cities, we can look at how underlying policies influence street tree distribution and the ways in which policy can support or prevent the incorporation of trees into public transportation infrastructure. Therefore, this study has several key research objectives. (a) To compare the number of trees along the streets with and without bus routes. (b) Identify and compare the spacing policies that influence street tree plantings on these different types of roads. (c) Analyze infrastructural factors such as street signs (d) and their impact on street tree plantings. Statistical analyses will explore these relationships (e) to propose suggestions for cities to adopt more supportive policies that enhance urban forestry along their transportation corridors.

Chapter 3

Methodology

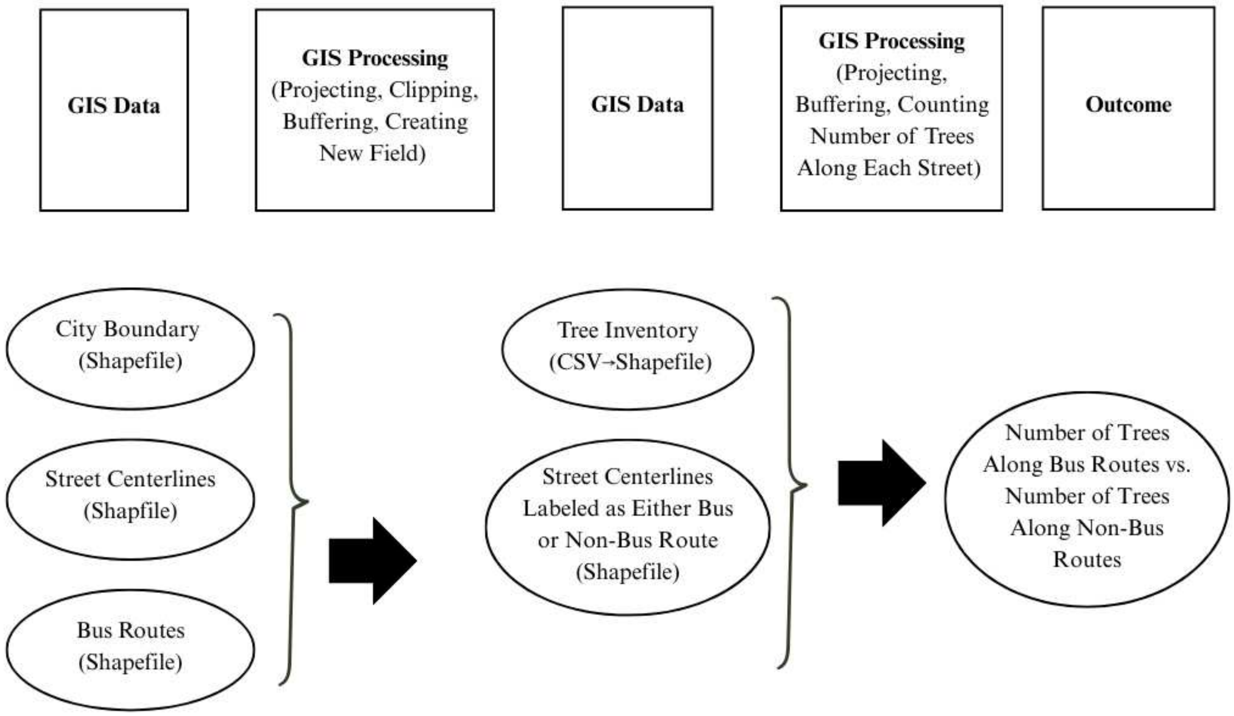

Figure 3.1: GIS Data Processing Protocol.

3.0.1 City Infrastructure Data

For 15 U.S. cities, publicly available geospatial data were used to investigate the relationship between street trees and the surrounding transportation systems and roadside infrastructure. The cities had to have had publicly available geospatial data for city boundaries, street centerlines, and bus routes to be included in the study. These data were collected from municipal sources including city, county, state or local public university geographic information system (GIS) Open

Data libraries. City data was prioritized followed by county, state and then university. Occasionally, the shapefiles for the bus routes came directly from the bus transportation organization. When city limit data was unavailable, shapefiles on city boundaries for the county or the state were used and the relevant city boundary was isolated. Data sets were clipped to each city's boundary to conduct analyses within a specific policy jurisdiction. GIS data sources are all available in the Supplemental Materials (A.2). To see the frequency with which each shapefile or GIS data is updated, follow the sources to the GIS data cited. The street centerline shapefiles were visually verified for spatial accuracy by overlaying them on the 'Streets' basemap in ArcGIS Pro and confirming alignment by eye. All data processing was performed using Python 3 in ArcGIS Pro (ESRI, 2023). Python scripts used in the study are available upon request.

Geospatial data were projected consistently using the appropriate Universal Transverse Mercator (UTM) coordinate system. To categorize roadways, a 10-meter buffer was created around polylines representing bus routes, and street centerlines were spatially joined with the buffer to determine whether they intersected it (Figure 3.2). This process was automated using ArcPy, labeling roads as 'Bus' or 'Non-Bus', respectively (Figure 3.1). Importantly, when an original road segment partially intersected the buffer, it was split at the intersection point, resulting in two or more modified segments—some labeled "Bus" and others "Non-Bus." Thus, the final unit of spatial analysis consisted of these modified road segments, defined as continuous portions of roadway that were either entirely within or entirely outside the bus route buffer. This splitting process ensured more precise classification of streets, capturing variation in transit adjacency along individual roadways. All segments were then used to calculate street tree density, defined as the number of trees/km of segment length. Segment-level density values were aggregated separately for "Bus" and "Non-Bus" categories to allow for comparisons within and across cities.

A 10-meter threshold was selected after evaluating multiple buffer distances, with the objective of identifying a value that balanced spatial precision with consistency in various urban contexts. A smaller buffer often failed to capture roads that were functionally associated with bus routes due to minor misalignment in the underlying spatial data, such as differences between the road centers and the geometries of the routes. In contrast, larger buffers tended to overgeneralize proximity, occasionally including parallel streets or unrelated intersections.

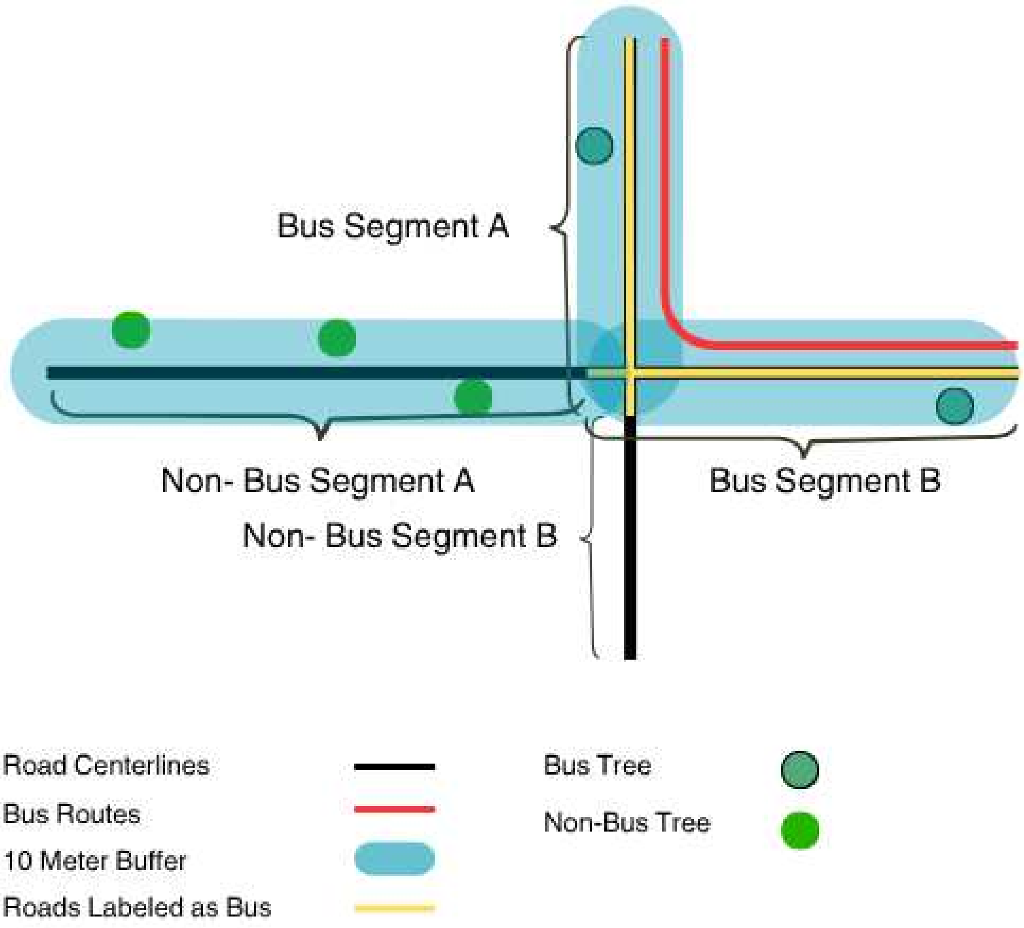

Figure 3.2: Classification of road segments based on proximity to bus routes. Road segments within 10 meters of a bus route were labeled as “Bus,” while those outside this threshold were labeled as “Non-Bus.” The 10-meter buffer is shown as a shaded zone around the bus route line. Small segments under 10 meters in length were removed to reduce misclassification before analysis. Trees within 10 meters of a road labeled as Non-Bus were labeled as Non-Bus Trees, and trees within 10 meters of a road labeled as bus were labeled as Bus Trees.

To address the occasional misclassifications of road segments as "Bus" due to brief spatial overlaps within the 10 meter proximity threshold, all road segments measuring 10 meters or less in length were excluded from the final analysis. This step helped minimize the influence of small, potentially erroneous segments introduced by buffer-based spatial joins. Although occasional misalignment between bus routes and road centerlines exceeded 10 meters in some cities, these instances were infrequent and did not justify varying the threshold between cities. The maintenance of a consistent distance parameter was prioritized to allow for standardized comparisons between cities and preserve the methodological integrity of the analysis.

In cities with publicly available GIS signage data (Buffalo, Denver, Detroit, Houston, Los Angeles, Madison, Sacramento, and Sioux Falls), a similar process of labeling "Bus" or "Non-Bus" was used to determine the number of signs along each road type. For the data sources of signage please reference Section A.3 in the Supplemental Materials. Unfortunately, GIS utility data was not readily available, with most cities' GIS departments citing safety concerns as a reason not to make utility data publicly available.

3.0.2 Street Tree Inventory Data

The street tree inventory dataset used for this study were a subset of data, obtained from McCoy et al. (2022), which contained over 5 million urban tree inventory records from 63 U.S. cities. From those 63 cities, the 15 cities with available bus route geospatial, street centerline and available municipal code data were included. The dataset from McCoy et al. (2022) contained information about the species, location, native status, and condition of each tree.

Each city underwent an identical cleaning and GIS processing protocol (Figure 3.1). Tree inventory data were converted from CSV into shapefile format for spatial analysis. After conversion, duplicate entries of the same tree, and entries related to vacant sites were removed from all inventories. To ensure comparability of analyses in different cities, geospatial data were projected consistently using the appropriate UTM coordinate system. The number of trees located along each segment was counted, and density was calculated as the number of trees/km of road segment length. These segment-level densities were then aggregated to calculate the mean density for Bus and Non-Bus road types across the study area.

3.0.3 Street Tree Spacing Guidelines

Spacing requirements for tree planting were obtained from city websites and municipal code documents. When documents were not publicly available online, municipal officials were contacted to request applicable requirements. Requirements for each city were collected and converted from feet to meters, although the original guidelines and their sources are provided in the Supplemental Materials (see A.1).

Table 3.1: Possible features listed under each spacing category based on municipal street tree guidelines.

Category	**Possible Features**
Spacing Between Trees	Large trees, Medium trees, Small trees, Overstory trees, Midstory trees, Understory trees, Shade trees, Ornamental trees, Upright form trees, Spreading form trees
Spacing from Utilities	Utility poles, Utility boxes, Underground utility lines, Water access covers, Power poles, Utility taps, Water meters, Sewer lateral, Water lateral, Gas lateral, Communications lines, Electrical lines, Electrical power poles, Water vaults, Gas meters, Electrical transmission towers, Water box, Gas box
Spacing from Traffic Controls	Stop signs, Street signs, Traffic control signs, Other traffic control devices, Traffic signals, Yield signs, Pedestrian lights
Spacing from Structures	Driveways, Driveway curb cuts, Driveway aprons, Benches, Trash cans, Tables, Poles, Parking stops, Curbs, Light poles, Fire hydrants, Alleys, Attached sidewalks, Mailboxes, Transit shelters, Pedestrian walkways, Building facades, Crosswalks, Bike racks, News racks, Parking meters, Street light bases, Building entrances/doorways, Railroad tracks, Building structures (general)
Spacing from Corners	Street intersections, Corners (general), Corners with traffic signals, Intersection apex, Non-controlled intersections, Cross streets (approaching and non-approaching corners)

To analyze and compare street tree spacing regulations, each city's spacing requirements were categorized based on nearby landscape elements that influence planting, including other trees, utilities, traffic control devices, other infrastructure/structures, and street corners (Table 3.1). The rationale for this quantification of regulations was to create a uniform way of comparing each city's tree planting guidelines. Within each category, all specified distances were summed to estimate the degree of planting constraint associated with each element. When guidelines provided a range (e.g., 9.14 - 15.24 m), the least restrictive value (the smallest distance) was used. A higher total score indicates more restrictive planting conditions and therefore may be expected to correlate with lower tree planting density.

This score should be thought of as a reflection of the severity of the spacing guidelines, not as the average distance a tree must be from an element. A score of 0 indicates that there is no specified regulation. The score for "Spacing from Trees" was determined using the minimum distance required between large (overstory) trees, since these trees were referenced most frequently. For "Spacing from Corners," the score was based on the minimum distance required from signalized intersections, because those are generally referenced most; if a city only provided distances for unsignalized intersections, those values were used instead.

3.0.4 Statistical Analyses

To model the density of street trees (trees/km) along road segments, we fit a Generalized Linear Model (GLM) with a Tweedie distribution and a log link function, using the `statsmodels` Python package (Seabold & Perktold, 2010). The Tweedie distribution, with a power parameter set to 1.5, was selected due to the non-normal, right-skewed, and zero-inflated nature of the tree density data (Figure A.1), making it well-suited for positive continuous outcomes with many zeros (Kokonendji et al., 2020).

During model fitting, street segments were weighted proportionally to their length divided by their city's total length. This approach maintained higher weights for longer segments while preventing cities with larger networks from disproportionately influencing the model. Weights were incorporated using the `freq_weights` argument in the GLM module.

The model included the following predictors: city, road type (Bus or Non-Bus), and spacing guideline restrictiveness, with categories as described in Table 3.1. The “city” variable was included as a categorical predictor to control for inter-city differences in urban forestry practices, socioeconomic context, and climate. Anaheim served as the reference category, as its total road tree density was closest to the dataset mean.

The initial model included all main effects and interaction terms between the bus route indicator and each spacing guideline category, to account for potential differences in the effect of regulations depending on road type. We then conducted iterative model refinement, removing predictors with high p-values ($p > 0.05$) one at a time. After each removal, we evaluated model performance using the Bayesian Information Criterion (BIC), where a lower BIC indicated improved fit (Neath & Cavanaugh, 2012).

Although some individual city predictors were not statistically significant ($p > 0.05$), excluding the city variable worsened the overall model fit, as indicated by an increase in BIC. A Wilks likelihood ratio test (Wilks, 1938) comparing the full and reduced models confirmed that including city as a predictor significantly improved model fit ($p < 0.001$). Therefore, the city variable was retained to account for location-specific effects.

To aid interpretation of the GLM coefficients, we computed marginal effects at the mean of the predictors (Bartus, 2005). These represent the expected change in tree density for a one-unit increase in each predictor (e.g., 1 meter of spacing), holding other variables at their mean values. Because the model includes interactions between bus route status and spacing guidelines, marginal effects were calculated separately for bus and non-bus routes to elucidate the net effects of regulations across road types.

To compare street tree densities between cities, we used Python's `pandas`, `numpy`, `matplotlib`, `seaborn`, `itertools`, and `statsmodels.stats.multicomp` packages. A Tukey Honestly Significant Difference (HSD) test was applied for pairwise city comparisons at a $p < 0.05$ significance level using the `pairwise_tukeyhsd` function. To visualize these comparisons, we generated Compact Letter Displays (CLDs), which assigned letters to cities such that those sharing the same letter did not differ significantly or were more similar (Piepho, 2018). Cities with different letters were statistically distinct, providing a concise summary of inter-city differences in street tree densities.

Chapter 4

Results

4.1 Comparing Street Tree Distribution by Street Type and City

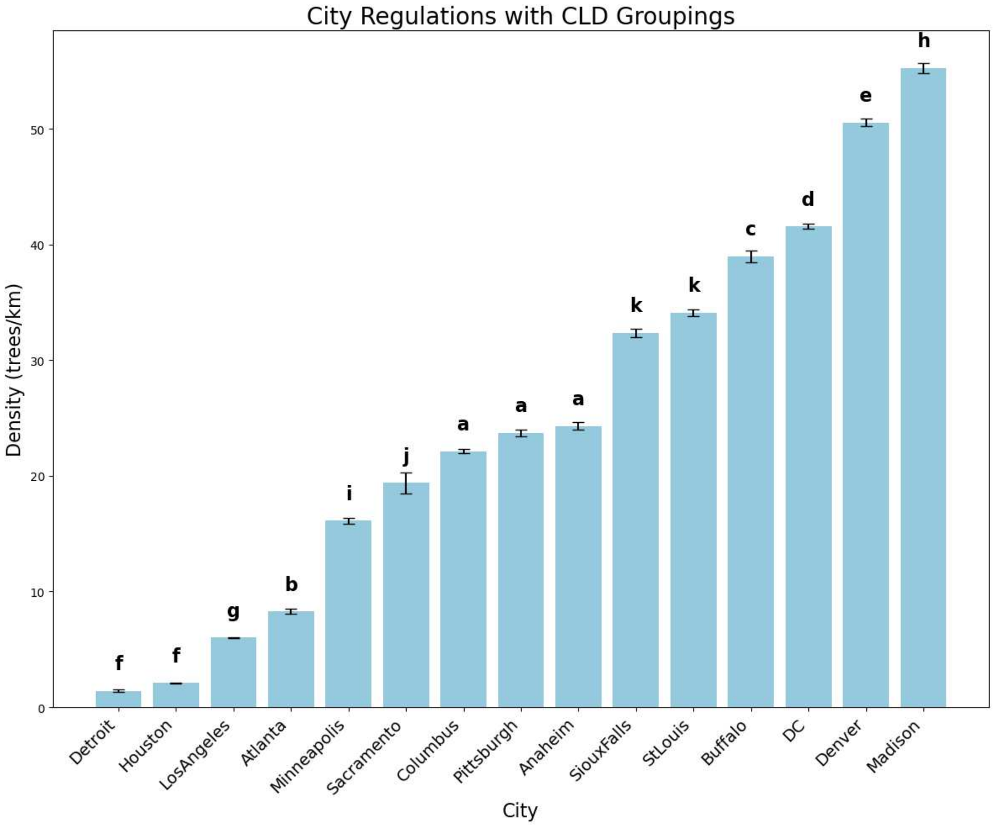

Figure 4.1: CLD showing groupings of cities based on Tukey HSD results.

We found that there were significant differences in overall street tree densities between most cities, with 11 unique groups identified through HSD testing (Figure 4.1). While a few pairs or trios of cities shared similar overall street tree densities (e.g., Columbus, Pittsburgh, and Anaheim), there was still substantial range in cities' densities, ranging from less than 2 trees/km in Detroit to over 50 trees/km in Madison.

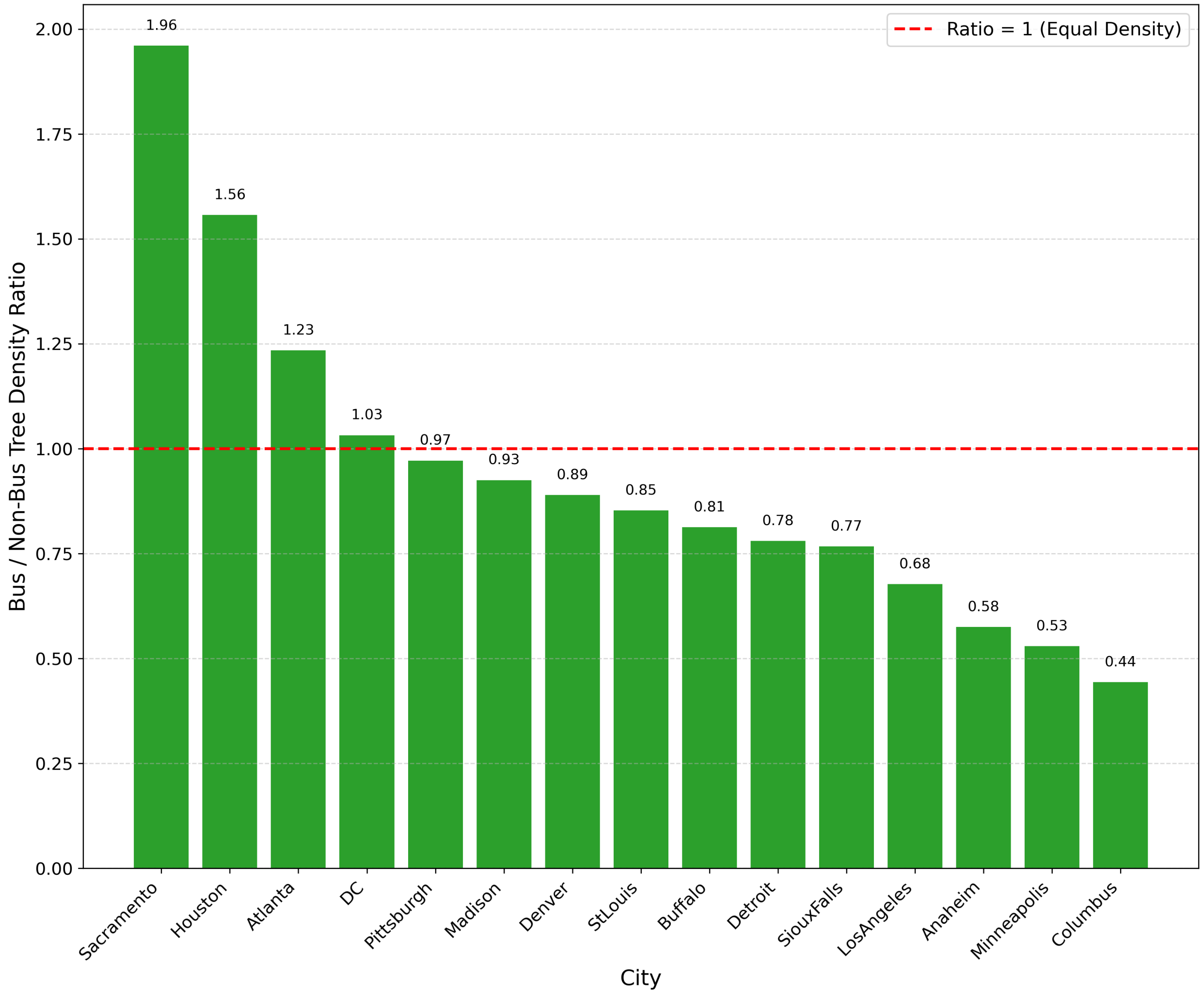

Figure 4.2: Comparison of tree density along bus and non-bus routes across cities, based on the ratio of linear tree density (trees/km) for bus routes to non-bus routes, showing variation in tree distribution between these two types of streets, with a dashed line indicating a ratio of 1, where tree densities are equal.

To understand how tree planting varies by street type, we also compared tree densities along bus and non-bus routes across cities (Figure 4.3). Further, by calculating the ratio of tree density (trees/km) on bus routes to that on non-bus routes, we found that 73% of the 15 cities studied have a bus/non-bus density ratio less than 1, meaning that trees are more concentrated along non-bus routes (Figure 4.2). The median bus-to-non-bus density ratio across all cities was 0.85, reinforcing the trend, further underscoring the overall trend of greater tree abundance along non-bus routes than bus route streets. Only four cities—Washington, DC, Atlanta, Sacramento, and Houston—had more trees along bus routes than on other streets.

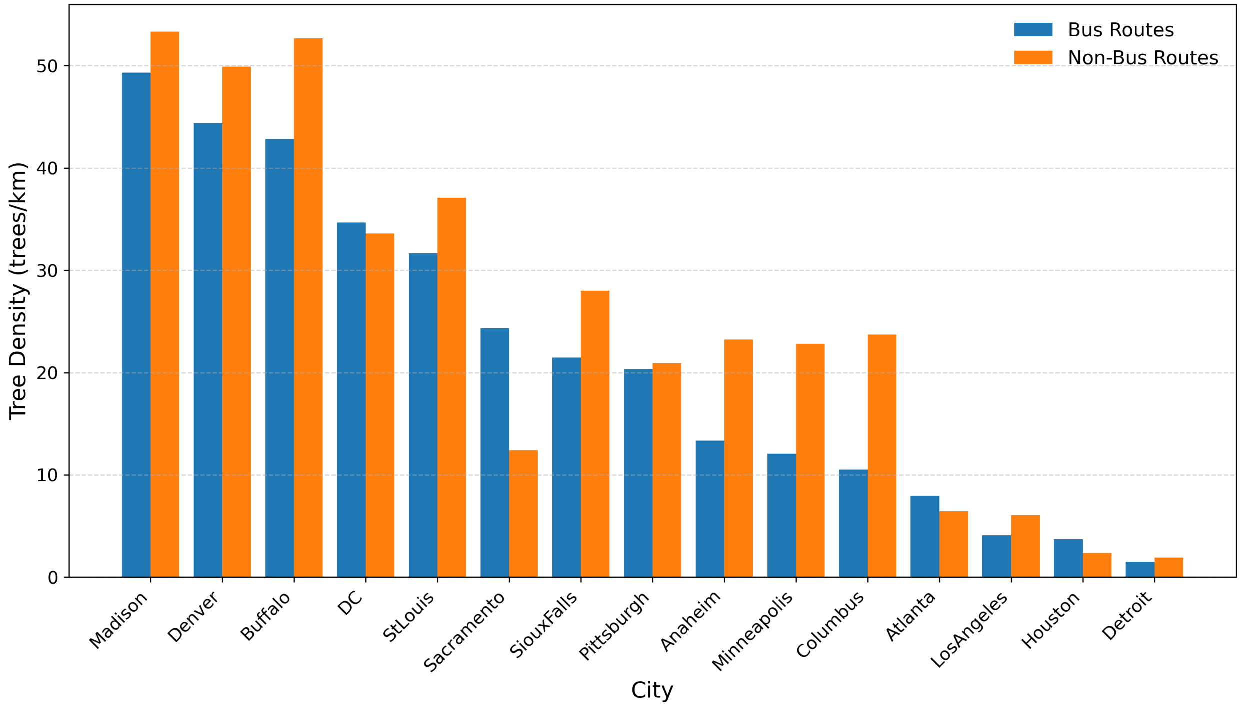

Figure 4.3: Tree density (trees/km) on bus and non-bus routes by city.

Table 4.1: Cumulative spacing requirements for tree planting among 15 U.S. cities (converted to meters from feet). 0 reflects no specified spacing requirement. The scores were not the average spacing requirement from a tree, but rather a score of severity in guidelines that can be used to compare across different cities.

City	Trees (m)	Utilities (m)	Traffic Controls (m)	Structures (m)	Corners (m)	Total (m)
Anaheim, CA	0.00	0.00	0.00	0.00	0.00	0.00
Atlanta, GA	7.62	0.00	0.00	0.00	0.00	7.62
Buffalo, NY	9.14	10.97	0.00	11.58	13.72	45.41
Columbus, OH	12.19	9.45	18.29	30.48	9.14	79.55
Washington, DC	10.67	0.00	24.38	13.72	12.19	60.96
Denver, CO	7.62	1.52	0.00	17.37	9.14	35.65
Detroit, MI	0.00	0.00	0.00	0.00	0.00	0.00
Houston, TX	0.00	0.00	0.00	6.10	0.00	6.10
Los Angeles, CA	7.62	14.02	15.24	55.78	13.72	106.38
Madison, WI	12.19	6.10	3.05	17.07	15.24	53.65
Minneapolis, MN	0.00	4.57	12.19	25.91	12.19	54.86
Pittsburgh, PA	9.14	3.05	9.14	0.00	9.14	30.47
Sacramento, CA	9.14	6.71	0.00	16.76	7.62	40.23
Sioux Falls, SD	12.19	0.00	12.19	11.58	9.14	45.10
St. Louis, MO	10.67	4.57	0.00	9.14	6.10	30.48

4.2 Tree Spacing Guideline Patterns

Spacing requirements similarly varied considerably among the 15 cities examined in this study (Table 4.1). Considering the broad categories of guidelines as outlined in Section 3.0.3, we found

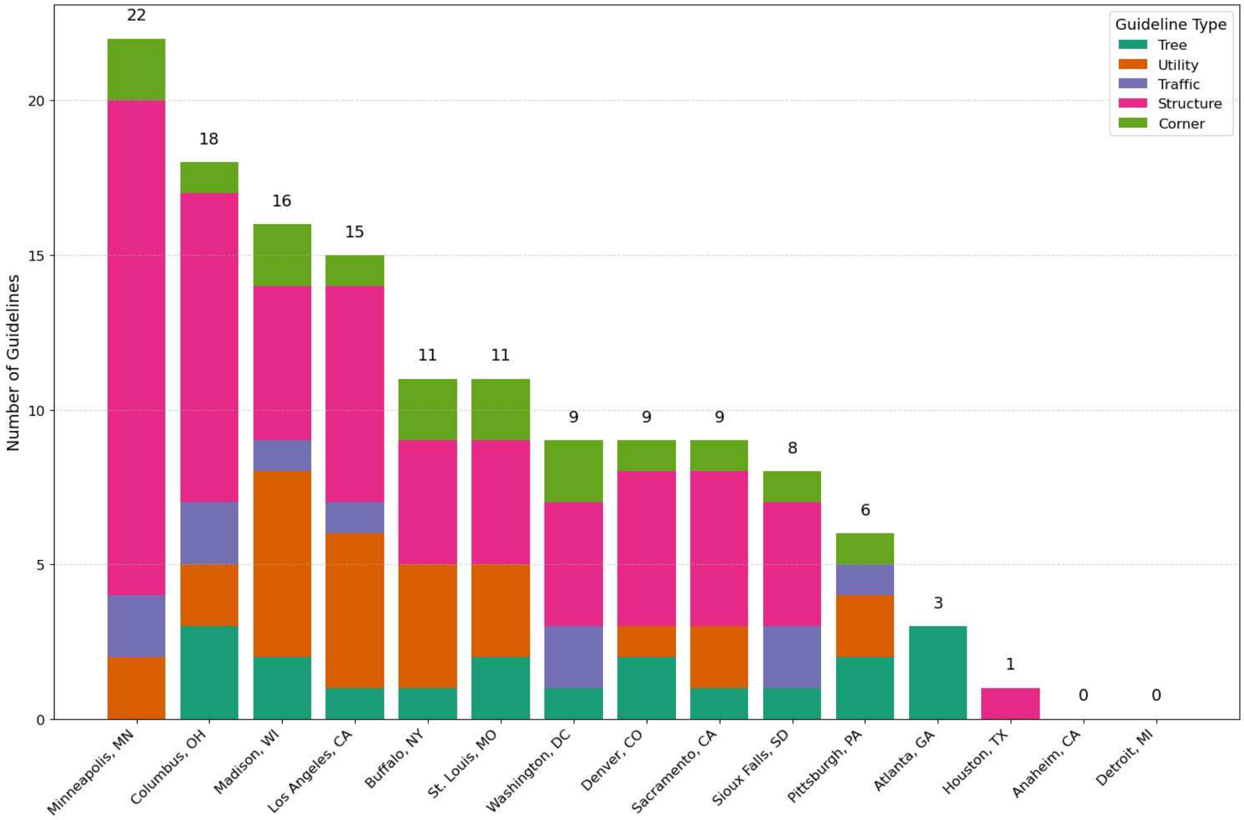

Figure 4.4: Number of Tree Planting Spacing Guidelines by Category.

most cities included guidelines for spacing between trees (11 cities), structures (11 cities), and corners (11 cities). Fewer cities had regulations for utilities (9 cities) and traffic controls (7 cities), suggesting that these factors may be addressed less frequently. The strictest spacing guidelines were found around structures, with a maximum distance of 55.78 meters (Los Angeles, CA).

There were 138 total rules across 15 cities, for an average of 9.2 regulations per city and a median of 9 regulations (Figure 4.4). Minneapolis had the highest number of regulations at 22 and Anaheim and Detroit had the lowest with 0 regulations. Across all cities, there were 16 regulations related to trees, 25 related to utilities, 12 for traffic control, 61 for structures, and 18 for corners. Structure-related requirements were most common, with 61 instances recorded. Within this category, driveways (including entrances, aprons, and curb cuts), fire hydrants, street lights (including light poles) and alleys (including alley entrances) were the most common structures with spacing guidelines. Guidelines for driveways, fire hydrants, and street lights were found in 10 out of 15 cities, while 6 out of 15 cities had regulations for alleys.

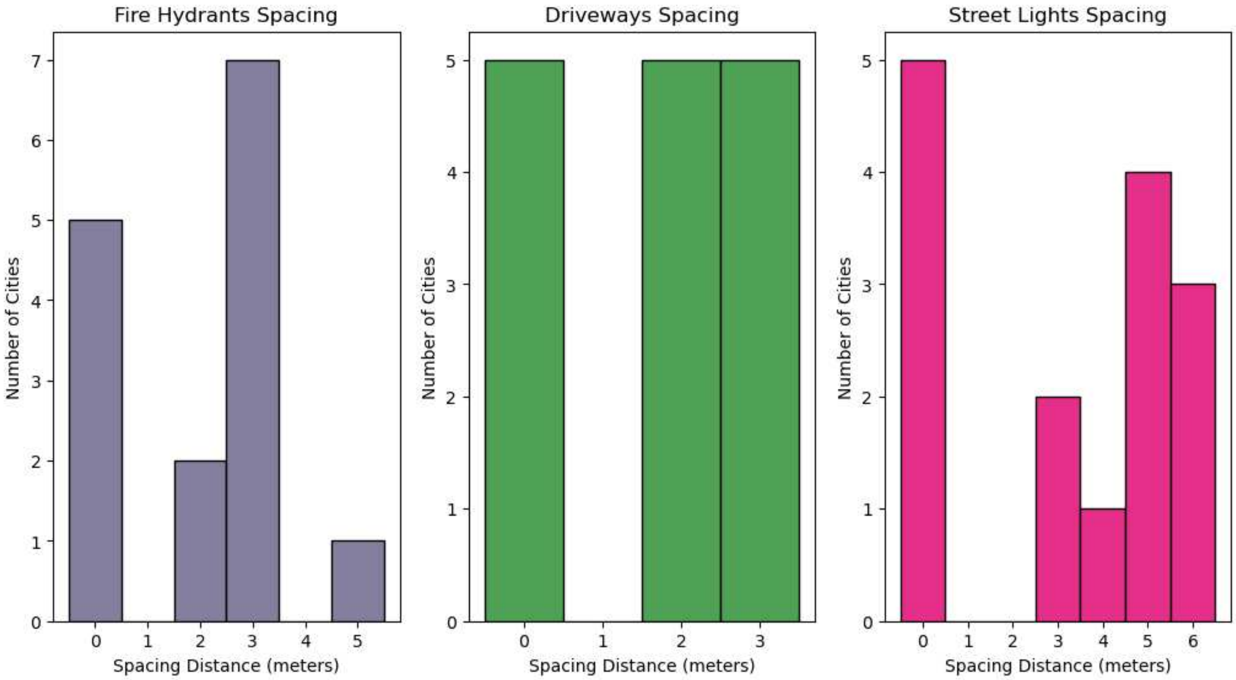

Figure 4.5: Frequency of Spacing Requirements for the Most Common Structures

Of the three most common spacing structure guidelines (driveways, fire hydrants, and street lights), no spacing guideline was consistent across all cities (Figure 4.5). Spacing from driveways ranged from 1.52–3.05 meters (1.52 m, 1.83 m, 2.44 m, and 3.05 m), with 4 out of the 10 cities requiring a minimum of 3.05 meters and 3 out of the 10 cities requiring a minimum of 1.52 meters. Spacing from fire hydrants was either 1.52, 3.05, or 4.57 meters, with 7 out of 10 cities requiring a minimum of 3.05 meters. Spacing from street lights ranged from 3.05–6.10 meters (3.05 m, 3.66 m, 4.57 m, and 6.10 m), with 4 out of 10 cities requiring a minimum of 4.57 meters and 3 out of 10 cities requiring a minimum of 6.10 meters.

Beyond these more consistently-regulated structures, 5 cities also had unique regulations (Table 4.2). In Columbus, OH, the guidelines included 3.05 meters of spacing for benches, trash cans, tables, poles, and parking stops. Denver, CO specified 2.13 meters for attached sidewalks. Los Angeles, CA provided a unique regulation for railroad tracks (30.48 meters). Madison, WI also had regulations for mailboxes and other hardscape items, both requiring 3.05 meters of spacing. Finally, Minneapolis, MN, included several unique spacing requirements such as 1.83 meters for pedestrian walkways and no trees at loading zones or bus stops.

Table 4.2: Spacing Requirements Mentioned by only one City.

City	Spacing from Structures
Columbus, OH	Benches: 3.05 m, Trash cans: 3.05 m, Tables: 3.05 m, Poles: 3.05 m, Parking stops: 3.05 m
Denver, CO	Attached sidewalks: 2.13 m
Los Angeles, CA	Railroad tracks: 30.48 m
Madison, WI	Mailboxes: 3.05 m, Other hardscape items: 3.05 m
Minneapolis, MN	Pedestrian walkways: 1.83 m, No trees at loading zones, No trees at bus stops, Crosswalks: 2.13 m, Bike racks: 1.52 m, News racks: 1.52 m, Parking meters: 1.52 m

4.3 Distribution of Urban Infrastructure Along Bus and Non-Bus Routes

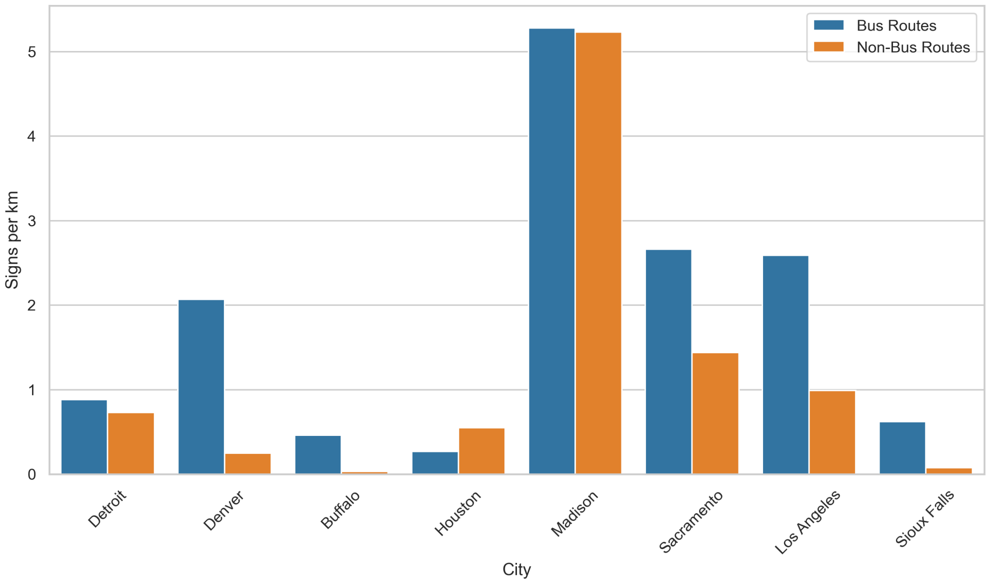

Figure 4.6: Sign Density by Street Type Across Cities. The graph shows the comparison of sign density along bus and non-bus routes in different cities.

Across the eight cities studied, bus routes generally had higher sign densities than non-bus routes, with Houston, TX being the only exception (Figure 4.6). However, the magnitude of this difference varied widely. For instance, in Detroit, bus routes had only about 20% more signs compared to non-bus roads. In cities like Los Angeles and Sioux Falls, however, the difference was more pronounced, with 160% and almost 700% more signs/km on bus routes versus non-bus routes, respectively. Overall, the average linear density of signs ranged from near zero to five signs/km across cities.

4.4 Spacing Guidelines Impact on Street Tree Density Along Bus Route Streets

Table 4.3: GLM Coefficients and Mean Marginal Effects for Bus Routes

Variable	Coefficient	Marginal Effect	p-value
City [Atlanta]	-1.00	-16.59	<0.001
City [Buffalo]	-0.02	-0.36	0.71
City [Columbus]	0.64	10.59	<0.001
City [DC]	0.11	1.76	0.001
City [Denver]	0.60	9.94	<0.001
City [Detroit]	-2.57	-42.51	<0.001
City [Houston]	-1.75	-28.95	<0.001
City [Los Angeles]	-0.22	-3.68	<0.001
City [Madison]	0.15	2.43	0.007
City [Minneapolis]	-0.35	-5.81	<0.001
City [Pittsburgh]	-0.79	-13.12	<0.001
City [Sacramento]	-0.31	-5.18	<0.001
City [Sioux Falls]	0.01	0.23	0.81
City [St. Louis]	0.39	6.44	<0.001
Along Bus Routes	0.20	-1.55	<0.001
Trees Spacing	-0.02	-0.33	0.002
Structures Spacing	-0.04	-0.70	<0.001
Traffic Control Spacing	-0.0079	-0.33	<0.001
Corners Spacing	0.12	1.91	<0.001
Utilities Spacing	-0.03	-0.49	<0.001

The final model included predictors for City (with Anaheim as the reference), whether the road segment is along a bus route (On Bus Route), spacing regulations for Trees, Structures, Traffic Controls, and Corners, as well as interaction terms between On Bus Route and each spacing regulation except for Corners. All of these predictors—except for two city levels—were identified as statistically significant predictors of street tree density (Table 4.3).

For streets with bus routes, tree density varied substantially across cities. Compared to Anaheim, Detroit and Houston had the largest negative marginal effects, with bus route segments hosting 42.51 and 28.95 fewer trees per bus road segment, respectively ($p < 0.001$). In contrast, Columbus and Denver had higher predicted tree densities, with marginal effects of +10.59 and +9.94 trees/km, respectively ($p < 0.001$).

We found the marginal effect of 'Along Bus Routes' was negative ($\text{ME} = -1.55$, $p < 0.001$), indicating that segments on bus routes are predicted to have 1.55 fewer trees/km on average compared to non-bus route segments, when controlling for all other factors.

For most regulation types, stricter guidelines were associated with a lower tree density along bus routes. Stricter tree spacing and traffic control spacing was associated with a modest 0.33 fewer trees per bus route road segment ($p = 0.002$ and $p < .001$). Stricter structure and utilities regulations were associated with an even lower street tree density (0.7 and 0.49 trees/km respectively).

In contrast, corner spacing was positively associated with tree density: each additional meter of allowable distance between trees and corners corresponded to 1.91 more trees per segment on average ($p < 0.001$). More broadly, we found cities without any corner spacing guidelines had a mean overall tree density of 8.3 trees/km. Cities with at least one corner spacing regulation (of any distance) had a mean overall tree density of 28.4 trees/km. This difference was statistically significant (Welch's t-test, $p = 0.006$).

4.5 Spacing Guidelines Impact on Street Tree Density Along Non-Bus Route Streets

Table 4.4: GLM Coefficients and Mean Marginal Effects for Non-Bus Routes

Variable	Coefficient (β)	Marginal Effect (ME)	p-value
City [Atlanta]	-1.00	-18.22	<0.001
City [Buffalo]	-0.02	-0.39	0.707
City [Columbus]	0.64	11.63	<0.001
City [DC]	0.11	1.93	0.001
City [Denver]	0.60	10.92	<0.001
City [Detroit]	-2.57	-46.69	<0.001
City [Houston]	-1.75	-31.79	<0.001
City [Los Angeles]	-0.22	-4.04	<0.001
City [Madison]	0.15	2.67	0.007
City [Minneapolis]	-0.35	-6.38	<0.001
City [Pittsburgh]	-0.79	-14.41	<0.001
City [Sacramento]	-0.31	-5.68	<0.001
City [Sioux Falls]	0.01	0.25	0.813
City [St. Louis]	0.39	7.07	<0.001
Trees Spacing	-0.02	-0.36	0.002
Structures Spacing	-0.04	-0.74	<0.001
Traffic Controls Spacing	-0.0079	-0.14	<0.001
Corners Spacing	0.12	2.09	<0.001

The same model used for the bus route outcomes was also used for the non-bus route outcomes. Cities also varied widely in predicted tree density, along non-bus routes (Table 4.4). Relative to

Anaheim, cities like Detroit and Houston showed the strongest negative associations, with 46.69 and 31.79 fewer trees/km per non-bus road segment, respectively ($p < 0.001$). In contrast, Columbus and Denver were associated with increases of 11.63 and 10.92 trees/km, respectively ($p < 0.001$). Several other cities also had statistically significant associations, with generally smaller effect sizes.

Spacing regulations had strong predictive power, with the exception of utilities spacing, which had no significant effect on tree density along non-bus roads. Most regulations were again associated with a decrease in tree density, though to different degrees than along bus routes. Tree spacing and structure spacing were associated with a slightly larger decrease in tree density along non-bus roads compared to bus routes (0.36 and 0.74 respectively), while utilities and traffic control spacing was associated with a smaller decrease in density (0.0 and 0.14 respectively). As with bus routes, corner spacing had the opposite effect: for each additional meter allowed between trees and corners, density increased by 2.09 trees/km ($p < 0.001$).

Chapter 5

Discussion

5.1 City-Specific Trends

Looking at overall street tree density, we found both widely varying marginal effects for each city and 11 distinct clusters through CLD analysis, highlighting how tree planting outcomes vary significantly by city. In general, these findings emphasize the heterogeneity of tree densities in cities. While restrictive guidelines generally suppressed planting density, we find tree densities are still heavily influenced by city-specific differences (e.g., climate, socioeconomic status, robustness of urban forestry programs, etc.), as consistent with the literature (Mejía et al., 2024; Schwarz et al., 2015; Wang et al., 2024). This variation points to the need for city-specific evaluations when projecting street tree densities and an evaluation of other factors controlling street tree density.

To assess whether street trees were more densely planted along bus routes compared to other streets, we analyzed tree density across the two road types. We found that most cities (73%) had significantly lower tree density along bus routes. In several cities, the difference was nearly twofold, perhaps reflecting the impact of land use patterns, with bus routes often running through a mix of residential and other land uses that may have lower tree cover. For example, transit routes typically serve areas with a substantial proportion of residential land use—one study found that, on average, transit routes included about 54% residential land use among other land-use categories (Demissie & Kattan, 2022). Previous research lends supports to this inference, having found that denser housing correlated with lower tree cover (Hilbert et al., 2019). Since buses tend to serve more densely populated neighborhoods, the observed lower tree density may reflect their location within areas of higher housing density. While much of the literature focuses on how land use affects tree cover in residential areas more generally, future research could extend this analysis to include public transit corridors and the specific types of residential areas they service.

Conversely, cities like Atlanta (1.23), Denver (0.89), and St. Louis (0.85) displayed more balanced tree distributions (Figure 4.2). Notably, Atlanta and Denver have minimal or no restrictions in most guideline categories. This regulatory flexibility may allow for more consistent planting along transit corridors. Recent scenario modeling, used to estimate potential canopy growth under different tree spacing scenarios, also found that flexible spacing assumptions can significantly increase the number of trees planted across various urban typologies, particularly when spacing guidelines are minimized (Martinez et al., 2025). Our findings, along with the existing literature, support the idea that easing certain spacing restrictions can increase density and evenness of the urban forest.

5.2 Spacing Guidelines, Street Trees and the City

Across all cities, we investigated how spacing regulations and polices influence street planting on both road types (bus and non-bus route streets). We found that street segments located on bus routes have an expected 1.55 fewer trees/km in tree density compared to non-bus route segments. This indicates that road type plays a significant role in shaping street tree density. This disparity may be explained by the fact that street trees already face numerous challenges, including design constraints (Mullaney et al., 2015), safety concerns (Bucsuházy et al., 2022), poor tree health outcomes (Roman & Scatena, 2011) and competition with other infrastructure (Egerer et al., 2024). These challenges are likely exacerbated along bus corridors, where increased infrastructure demands (such as more signage) add further constraints, as evidenced by a higher frequency of signs on bus routes compared to non-bus streets (Figure 4.6).

Moreover, we observe that there would be 0.33 fewer trees/km for every meter increase in Traffic Control Spacing regulations along bus routes compared to only 0.14 fewer trees/km along non-bus routes. This again likely reflects the impact of higher density traffic controls found along bus corridors. Together, these findings highlight how greater sign density combined with rigid spacing requirements reduces available planting opportunities, illuminating the interconnected relationship between spacing regulations, infrastructure distribution, and street tree density.

Most types of spacing regulations along bus routes were also generally associated with a lower tree density. For example, Trees Spacing, Structures Spacing, Traffic Control Spacing, and Utilities Spacing all had negative marginal effects for bus route streets. Hence, we find most types of regulations limit total street tree plantings along bus route streets. Cities should be mindful of how increasing the strictness of their Tree Spacing, Structures Spacing, and Traffic Control Spacing regulations could negatively impact their overall ability to plant street trees along bus routes, especially in light of new scenario modeling research suggesting minimizing distancing rules increase total tree planting potential (Martinez et al., 2025).

A similar result was found for non-bus route streets as well, with these same types of spacing regulations being negatively associated with street tree density. In general, these regulations decrease the density of trees along roads, regardless of the presence of a bus route; however, the amount of which the regulation decreased density depends on the type of road. This was most noticeable in the effect Utilities Spacing had on tree density along bus route streets as compared to non-bus route streets. While Utilities Spacing regulations were not a significant predictor along non-bus routes, it was associated with 0.49 fewer trees/km along bus route streets with each 1-meter increase in Utility Spacing regulation. As we were not able to obtain city utility data, we cannot definitively say that this difference in marginal effect is a result of utility infrastructure being more tightly clustered around bus routes. However, city planners and urban foresters could perform this analysis with their own city's proprietary data to examine this connection further, using an approach similar to the one we used to draw the relationship between infrastructure distribution, specific types of spacing regulation, and tree density.

These findings highlight the need for dynamic and adaptive regulations that evolve alongside the urban forest, particularly in areas of infrastructural complexity (such as transit corridors). This relationship between infrastructure and opportunities for urban treen planting has been documented in New York City through the lens of the "practical canopy". This framework emphasizes the interconnectedness of tree canopy and infrastructural needs and restrictions (Treglia et al., 2022). We similarly find this relationship between infrastructure and street tree density across multiple

U.S. cities, and further illustrate the infrastructural connection between road type, such as transit systems.

Our analysis also revealed that the Corners Spacing regulations had a positive and statistically significant effect on tree density for both bus route streets (ME=1.91) and non-bus route streets (ME=2.09), indicating that for each meter increase in corner-related regulation, the expected tree density increases by 1.91 trees/km and 2.09 trees/km for bus route and non-bus route street segments respectively. This finding suggests that street segments with more stringent corner regulations tend to support higher tree densities. This finding may seem counterintuitive, with stricter corner guidelines being correlated with more street tree plantings. However, these regulations could reflect a broader commitment to maintaining and expanding the urban forest, serving as a protective measure or an indicator of proactive tree management (Hilbert et al., 2019; Sousa-Silva et al., 2023). A preliminary result that may support this theory was the significant difference in overall tree density between cities with any corner spacing guidelines and those without (p = 0.006). This finding illustrates that just the presence of any corner spacing regulation, regardless of severity, is associated with higher density. Future research, perhaps by controlling explicitly for robustness of a city's urban forestry program, is still needed to solidify the reasoning behind this positive relationship between density and corner spacing regulation.

From this analysis, we saw that the type of regulation impacts street tree planting differently, ranging from positive to negative associations. We also saw that regulations influence street tree densities differently along bus route and non-bus route streets, aligning with existing research that has demonstrated street tree density and distribution vary not only by city and climate zone, but also by street hierarchy and local urban form, suggesting that infrastructure, planning norms and regulatory approaches can yield uneven tree coverage across different street classifications (Smart et al., 2020). Thus, city planners and urban foresters must consider, not just how spacing regulations impact tree density in bulk, but also how the specific type of regulation, furthers or hinders their tree density targets along bus and non-bus roads individually.

5.3 Safety Trade-offs in Street Tree Placement

While this research primarily focuses on the benefits of increasing street tree density, many municipal regulations may be restricting tree planting near intersections and key infrastructure to preserve sight lines for drivers and pedestrians. The presence of trees near roadways can present safety concerns in the event of a crash. Fixed-object collisions, particularly involving trees, are associated with a higher probability of severe or fatal injury (Holdridge et al., 2005).

However, research also suggests that increasing tree density and canopy cover can actually improve driver safety by reducing vehicle speeds and improving driver attentiveness (Zhu & Newnam, 2022). Tree-lined streets have been shown to create a psychological sense of enclosure, which encourages more cautious driving behavior, ultimately leading to fewer crashes (Marshall P.E. et al., 2018). This trade-off highlights the need for strategic tree placement, balancing safety concerns with the benefits of traffic calming and pedestrian safety. Despite this, there remains a notable gap between urban forestry practices and transportation engineering guidelines—particularly in how clear zones (areas around roads that are kept free of fixed objects vehicles might collide with) are defined and implemented in city environments (Wolf & Bratton, 2006).

As we have shown in this work, current municipal regulations vary widely, with some cities imposing strict regulations while others have none. This aligns with previous research that has shown that spacing guidelines vary greatly by cities without clear differences in the guidelines effectiveness on safety (Messier, Margulies, & Wilson, 2025). These inconsistencies suggest that many regulations may not be based on safety data or evidence; however there is existing literature for which cities can utilize to help design these regulations in regards to traffic safety concerns (Wolf, 2005). Additionally, cities can weigh these design recommendations while still encouraging more tree planting, in order for cities to reap the benefits of street trees, particularly in areas with bus corridors where trees can improve pedestrian comfort and reduce urban heat (Egerer et al., 2024; D. E. Pataki et al., 2021; Zhu & Newnam, 2022).

5.4 Toward More Deliberate Street Tree Regulations

In addition to safety considerations, municipal regulations should consider the long-term health and viability of street trees. Currently, municipal regulations on the placement of street trees vary widely, with regulations not necessarily being rooted in the biological needs of trees or the practical requirements for maintaining other infrastructure. These wide-ranging guidelines coupled with the disproportionate tree densities by road type within cities indicate that spacing regulations might be limiting urban canopy or failing to provide trees with conditions needed to reach maturity. Roman et al., (2020) highlighted the importance of balancing the benefits and challenges of urban trees, emphasizing that poorly planned regulations can lead to unintended consequences, such as increased maintenance cost or tree removal due to conflicts with infrastructure. Instead of arbitrary distance requirements, cities should establish guidelines that reflect both the ecological needs of trees (Roman et al., 2013) and the practical considerations for maintaining urban infrastructure, especially as cities have spent considerable funds addressing conflicts between tree roots and infrastructure (Randrup et al., 2003).

It is important to note that the number of trees is only part of the dynamic, having robust and mature trees are also essential for maximizing the urban canopy and the associated benefits (Livesley et al., 2016). While street trees have been shown to grow faster, they have higher mortality (Smith et al., 2019), future research should examine the health and size of street trees along bus route streets as compared to non-bus route streets to see if commuters are receiving the full services of mature trees. Since crown dimensions are strongly correlated with a tree's diameter at breast height (DBH), DBH can serve as a useful proxy for estimating canopy size and associated benefits (Lockhart et al., 2005) and hence can be used as a metric to compare tree maturity along different road types.

Research also suggests that closer tree spacings may accelerate canopy development, potentially achieving target canopy cover more quickly than wider spacings (Aryal et al., 2021). To ensure both tree health and infrastructure longevity, regulations should be designed around species-specific spacing needs and provide enough clearance for maintenance without requiring removal or damage to the tree. Thoughtful planning can prevent conflict between tree roots and underground utilities or avoid unnecessary removals when sidewalks or roadways need repairs, and subsequent incursion of costs (Vogt et al., 2015). By developing regulations that integrate research-backed best practices into regulatory frameworks, cities can create more resilient urban forests while minimizing future conflicts between trees and the built environment (Roman et al., 2020). Future studies may seek to perform a species-specific analysis to investigate how tree type and city ordinances interact to shape the urban forest.

These findings highlight the extent to which policy (specifically street tree planting guidelines) influences the physical landscape of urban streets. Given the environmental and social benefits of urban trees—especially for residents reliant on public transportation—ensuring equitable tree distribution along transit corridors is essential to sustainable urban development.

Street tree planting is a common municipal strategy for increasing urban canopy, since there are fewer barriers planting in public rights-of-way; however, just planting more and without specific community goals can inadvertently reinforce existing inequities in the urban forest (Conway et al., 2011). Anderson et al. (2023) found that in Baltimore, MD, street trees significantly increased citywide biodiversity and biomass, adding an average of six unique species per site. However, these benefits were concentrated in more affluent and denser neighborhoods, suggesting that current street tree investment strategies may be inadvertently reinforcing disparities in urban forest distribution (Anderson et al., 2023). Moreover, a case study of two Los Angeles neighborhoods found that less restrictive guidelines could minimize the disparity in trees quantity between the neighborhoods and that more restrictive guidelines limited more tree planting in the low-income neighborhood (Messier, MacDonald, & Wilson, 2025). This highlights the importance of moving away from default planting approaches toward more intentional strategies, such as linking tree planting with public programs like transit that prioritize equitable access to urban forest benefits. Municipal codes can serve as policy tools to guide this shift, ensuring that tree planting supports shared infrastructure and public space rather than overinvesting in already well-resourced areas.

Research conducted in cities in Alabama has already shown that most local officials consider urban trees very important, often valuing their socioeconomic benefits more than their ecological functions (Zhang & Zheng, 2012). Integrating urban forestry into transit planning could therefore be a compelling strategy, leveraging both ecological and socioeconomic benefits to foster more equitable urban environments.

However, municipal officials and urban foresters might struggle with developing municipal codes around street tree planting, as they try to balance competing priorities and sustainability goals of their city (Bassett, 2024). Perceptions of risk and liability among municipal employees also significantly influence urban forest management practices (Judice et al., 2023). Additionally, successful urban forest management have been found to be dependent on the increasingly collaborative partnerships between local governments and nongovernmental organizations; however, challenges such as shifting political priorities, funding instability, and departmental silos has been found to be barriers (Doucet et al., 2024). These barriers may impede the development of comprehensive municipal regulations that can wholistically address multiple city goals.

Lastly, street tree spacing guidelines often reflect negotiations among municipal departments—such as transportation, utilities, and urban forestry—each advocating for their own priorities (Cadaval et al., 2024). These negotiations are shaped by power dynamics, and groups with greater institutional influence often prevail, reinforcing patterns of underinvestment in less politically powerful neighborhoods (Pincetl, 2010). This illustrates how technical decisions are fundamentally governance choices that shape urban forest equity.

5.5 Limitations and Future Research

This research utilized a tree dataset originally compiled by McCoy et al. (2022), based on data developed by municipalities. These municipal datasets were primarily intended for planning and management purposes rather than scientific research, which presents a potential limitation. However, McCoy et al. followed standardized search protocols and applied extensive data cleaning procedures when assembling the dataset. These procedures included harmonizing health ratings, correcting taxonomic errors, and geocoding missing spatial information, which enhance the dataset's reliability for research use. Details on their cleaning methodology is available in their paper. A further limitation is the variation in the original tree data collection dates and update frequencies across the different city inventories. Nevertheless, all data were compiled concurrently and underwent consistent processing, which helps reduce relative biases between cities.

It is also important to note that, even within a single city, supporting datasets—such as street centerlines, bus routes, and infrastructure records—were developed for operational and planning uses and may not have been updated on the same schedule. Despite this, the versions used in this study represent the most recent data available at the time of download, all of which occurred between January 2024 and March 2025.

Moreover, while this study finds that street tree planting regulations can help explain some variation in street tree density across cities, they are not the sole determinant. For example, cities like Anaheim and Minneapolis exhibit similarly low tree densities along bus routes (bus/non-bus tree density ratios of 0.58 and 0.53, respectively), despite having markedly different regulatory frameworks. Anaheim lacks formal spacing guidelines in all five regulatory categories (Table 4.1), while Minneapolis has moderate to high requirements in several areas, such as spacing from traffic controls and corners. This contrast raises important questions for future investigation: To what extent do physical constraints imposed by regulations limit tree planting in transit corridors? How do other factors, such as institutional priorities, available funding, or the physical design of streets, interact with regulations to shape the layout of the urban forest?

Future research could investigate some of these additional factors influencing street tree distribution, including municipal funding allocations, the presence and priorities of urban forestry master plans, long-term maintenance challenges specific to trees along bus corridors, and the role of community-led greening initiatives. Examining how regulatory frameworks align with broader climate adaptation strategies may also offer valuable insights into how cities can balance transit infrastructure with urban forestry goals. Further, exploring whether observed patterns in DBH (tree size and health) persist across different species, planting conditions, or cities with varying levels of investment in transit-oriented greening could help contextualize the findings. To maximize the benefits of urban trees—especially in relation to public transit—it is critical that trees are able to mature and reach sizes that provide the greatest ecosystem services.

Lastly, future work could also examine whether tree planting is systematically de-prioritized along transit corridors in favor of residential areas, where conflicts with infrastructure like signage and utilities are less frequent. Investigating these dynamics across a larger sample of cities and including qualitative data from planners or urban foresters may help clarify the relative influence of regulatory frameworks versus other operational or spatial constraints on urban forestry strategies.

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Appendix A

Supplemental Materials

A.1 Expanded Municipal Spacing Regulations and Codes for Street Tree Plantings

A.1.1 Anaheim, CA

Anaheim had very few mandated regulations. When reaching out to Anaheim's Public Utilities department, they provided a link (https://codelibrary.amlegal.com/codes/anaheim/latest/anaheim_ca/0-0-0-51679) and a PDF of Anaheim's Chapter 13.12 Street Trees section. No spacing requirements or minimums were listed in the chapter.

A.1.2 Atlanta, GA

In total, Atlanta has only 3 guidelines around spacing requirements for street tree planting. These guidelines are found in the Tree Protection Ordinance: (https://www.atlantaga.gov/home/showdocument?id=58814&t=638169031069792768). Atlanta has tree requirements for how many trees must be planted within a certain range of space.

Table A.1: Atlanta, GA's Street Tree Planting Guidelines (in meters)

Object	**Spacing Requirement**
Overstory trees	7.6 meters minimum
Midstory trees	6.1 meters minimum
Understory trees	4.6 meters minimum

A.1.3 Buffalo, New York

In total, Buffalo has 11 guidelines around spacing requirements for street tree planting. Street tree planting guidelines for the City of Buffalo are available from the Bureau of Forestry: (https://www.buffalony.gov/358/Bureau-of-Forestry). The City of Buffalo's Street Tree Planting Standards was developed by the Department of Public Works, Parks and Streets: Division of Parks and Recreation, dated March 2011.

Table A.2: Buffalo, NY's Street Tree Planting Guidelines (in meters)

Object	Spacing Requirement
Between trees	9.1 meters minimum
Utility poles	4.6 meters minimum
Light poles	4.6 meters minimum
Fire hydrants	4.6 meters minimum
Utility boxes	4.6 meters minimum
Corner with traffic signal	13.7 meters minimum
All corners	10.7 meters minimum
Driveway curb cuts	1.5 meters minimum
Underground utility lines	0.9 meters minimum
Water access covers	0.9 meters minimum
Other (etc.)	0.9 meters minimum

A.1.4 Columbus, Ohio

In total, Columbus has 18 guidelines around spacing requirements for street tree planting. Minimum tree spacing is listed under the Columbus Tree Technical Manual housed within the Department of Recreation and Parks: (https://columbusrecparks.com/wp-content/uploads/2024/05/ColumbusTreeTechnicalManual-May2024.pdf).

Table A.3: Columbus, OH Street Tree Planting Guidelines

Object	**Spacing Requirement**
Large class trees	12.19 meter minimum
Medium class trees	9.14 meter minimum
Small class trees	6.10 meter minimum
Curbs	3.05 meter minimum
Parking stops	3.05 meter minimum
Poles	3.05 meter minimum
Benches	3.05 meter minimum
Trash can	3.05 meter minimum
Tables	3.05 meter minimum
Light poles (from edge of mature canopy)	3.05 meter minimum
Power poles	7.62 meter minimum
Street intersections	9.14 meter minimum
Driveways	3.05 meter minimum
Alleys	3.05 meter minimum
Stop signs	15.24 meter minimum
Street signs	3.05 meter minimum
Fire hydrants	3.05 meter minimum
Utility taps	1.83 meter minimum

A.1.5 Washington, DC

In total, DC has 9 guidelines around spacing requirements for street tree planting. Minimum tree spacing is listed under the Urban Forestry of the District Department of Transportation's Planting Specifications: https://ddot.dc.gov/sites/default/files/dc/sites/ddot/publication/attachments/tree_planting_specifications.pdf.

Table A.4: Washington, DC Street Tree Planting Guidelines (in meters)

Object	Spacing Requirement
Spacing between trees	10.67–12.19 meters minimum
Intersections	12.2 meters minimum
Stop signs	12.2 meters minimum
Other traffic control devices	12.2 meters minimum
Non-controlled intersections	7.6 meters minimum
Driveways	3.0 meters minimum
Alleys	3.0 meters minimum
Light poles	4.6 meters minimum
Fire hydrants	3.0 meters minimum

A.1.6 Denver, Colorado

In total, Denver has 9 guidelines around spacing requirements for street tree planting. Minimum tree spacing is listed under the Office of the City Forester's Tree Resources for Property Owners housed within the Department of Parks & Recreation: https://denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Parks-Recreation.

Table A.5: Denver, CO's Street Tree Planting Guidelines

Object	Spacing Requirement
Shade trees	1.52 meters minimum
Ornamental trees	7.62 meters minimum
Curb at intersections	9.14 meters minimum
Street lights	6.10 meters minimum
Alleys	3.05 meters minimum
Driveways	3.05 meters minimum
Fire hydrants	3.05 meters minimum
Attached sidewalks	2.13 meters minimum
Water meters	1.52 meters minimum

A.1.7 Detroit, MI

Detroit did not provide specific street tree planting spacing guidelines in the available ordinances. When reaching out to the City of Detroit's Office of Sustainability, they provided local ordinances related to trees and landscaping. However, no specific spacing requirements or minimums were listed in the documents for street tree planting.

A.1.8 Houston, TX

Houston had very few mandated regulations. When reaching out to Houston's Planning & Development Department, their Community Engagement Planner, Teresa Fetter Geisheker, emailed "Houston is known for a low level of mandated regulations, which we feel has helped us stay nimble and effective to maximize market conditions. We do, however, have ordinances that are enforced, although we don't specify many of the criteria [which have been used by other municipalities . . .]."

However, street tree planting guidelines were available in the Tree Planting Guide by the Houston Area Urban Forestry Council: https://www.houstontx.gov/police/cpted/planting_information/Tree_Planting_Guide_Booklet.pd. Houston has also published Tree and Shrub Requirements: https://www.houstontx.gov/planning/DevelopRegs/tree_shrub.html.

Table A.6: Houston, TX's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Structures	3.05, 4.57, or 6.10 meters minimum (depending on tree size)

A.1.9 Los Angeles, CA

In total, Los Angeles has 15 guidelines around spacing requirements for street tree planting. The City of Los Angeles's Urban Forestry Division named StreetLA housed within the Bureau of Street Services has published Tree Spacing Guidelines: https://streetsla.lacity.org/sites/default/files/BSS_TREE_SPACING_GUIDELINES.pdf.

A.1.10 Madison, WI

In total, Madison has 16 guidelines around spacing requirements for street tree planting. Street tree planting guidelines were unavailable by Google searches or housed on the City of Madison's website. Guidelines were obtained by emailing Madison's Forestry department. The City Forester,

Table A.7: Los Angeles, CA's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Trees	25' to 45' minimum
Water meter	6' minimum
Water vaults	6' minimum
Catch basins	6' minimum
Gas meters	8' minimum
Driveway aprons	8' minimum
Transit shelters	10' minimum
Fire hydrants	10' minimum
Pedestrian lights	15' minimum
Street lights	20' minimum
Electrical power poles	20' minimum
Alley entrances	20' minimum
Traffic control device	50' minimum
Unsignalized intersections	45' minimum
Railroad tracks	100' minimum

Ian Brown, responded by attaching guidelines that are "generally referenced". Brown also noted that they "[...] been able to increase the distance away from underground utilities to 5 feet and are in conversation to potentially increase it further".

Table A.8: Los Angeles, CA's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Trees	7.62 to 13.72 meters minimum
Water meter	1.83 meters minimum
Water vaults	1.83 meters minimum
Catch basins	1.83 meters minimum
Gas meters	2.44 meters minimum
Driveway aprons	2.44 meters minimum
Transit shelters	3.05 meters minimum
Fire hydrants	3.05 meters minimum
Pedestrian lights	4.57 meters minimum
Street lights	6.10 meters minimum
Electrical power poles	6.10 meters minimum
Alley entrances	6.10 meters minimum
Traffic control device	15.24 meters minimum
Unsignalized intersections	13.72 meters minimum
Railroad tracks	30.48 meters minimum

A.1.11 Minneapolis, MN

In total, Minneapolis has 22 guidelines around spacing requirements for street tree planting. The City of Minneapolis's official website has published a Street Design Guide. Under section 3.3 Boulevards and Furnishing, subsection D Street Trees, planting guidelines were provided: https://sdg.minneapolismn.gov/design-guidance/boulevards-and-furnishings/street-trees.

Table A.9: Minneapolis, MN's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Cross street (approaching corner)	12.19 meters minimum
Stop signs	6.10 meters minimum
Traffic signals	6.10 meters minimum
Pedestrian level light bases	3.05 meters minimum
Utility poles	3.05 meters minimum
Fire hydrants	3.05 meters minimum
Alleys	1.83 meters minimum
Driveways	1.83 meters minimum
Pedestrian walkway width	1.83 meters minimum
Building facades	1.22 meters minimum
Loading zones (clear zone)	Not allowed
Bus stops (clear zone)	Not allowed
Cross street (non-approaching corner)	6.10 meters minimum
Street light bases	3.66 meters minimum
Crosswalk	2.13 meters minimum
Bike racks	1.52 meters minimum
News racks	1.52 meters minimum
Utility boxes	1.52 meters minimum
Transit shelters	1.52 meters minimum
Parking meters	1.52 meters minimum
Street curbs	0.61 meters minimum
Building entrances or doorways	0.61 meters minimum

A.1.12 Pittsburgh, PA

In total, Pittsburgh has 6 guidelines around spacing requirements for street tree planting. The City of Pittsburgh's official website has published a Planting Site Analysis Check List (listing spacing requirements for street tree plantings). The Check List is housed under the Forestry Division in the Public Works Department: https://www.pittsburghpa.gov/files/assets/city/v/1/parks/documents/08_planting_site_analysis.pdf.

Table A.10: Pittsburgh, PA's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Upright trees	6.10 meters minimum
Spreading form trees	9.14 meters minimum
Water boxes	1.52 meters minimum
Gas boxes	1.52 meters minimum
Stop signs	9.14 meters minimum
Intersection apexes (no stop sign)	9.14 meters minimum

A.1.13 Sacramento, CA

In total, Sacramento has 9 guidelines around spacing requirements for street tree planting. Information on the guidelines were obtained by reaching out to the City Urban Forester of Sacramento, CA in the Department of Public Works, Urban Forestry.

Table A.11: Sacramento, CA's Street Tree Planting Guidelines

Object	**Spacing Requirement**
Trees	12.19 meters minimum, range of 9.14-15.24 meters
Intersections	7.62 meters minimum
Driveways	1.52 meters minimum
Fire hydrants	1.52 meters minimum
Buildings	1.52 meters minimum
Street lights	3.05 meters minimum
Utility poles	3.05 meters minimum
Utility lines	3.66 meters minimum
Big towers	9.14 meters per foot of tower

A.1.14 Sioux Falls, SD

In total, Sioux Falls has 8 guidelines around spacing requirements for street tree planting. Street tree planting guidelines were available under the Permits page of Sioux Falls's official city website: https://www.siouxfalls.gov/business-permits/permits-licenses-inspections/permits/tree-planting-permit.

Table A.12: Sioux Falls, SD's Street Tree Planting Guidelines

Object	Spacing Requirement
Curb	0.91 meters minimum
Trees	12.19 meters minimum (except where otherwise permitted)
Fire hydrants	3.05 meters minimum
Driveways	3.05 meters minimum
Streetlights	4.57 meters minimum
Corners	9.14 meters minimum
Stop/yield signs	6.10 meters minimum
Traffic signals	6.10 meters minimum

A.1.15 St Louis, MO

St Louis had 11 guidelines around street tree planting. Street tree planting guidelines were provided by the City of St. Louis by their Parks, Recreation and Forestry Department: https://www.stlouis-mo.gov/government/departments/parks/forestry/documents/street-tree-information.cfm.

Table A.13: St. Louis, MO's Street Tree Planting Guidelines

Object	Spacing Requirement
Large canopy trees	10.67 meters minimum
Small understory trees	6.10 meters minimum
Street corners	6.10 meters minimum
Intersections	6.10 meters minimum
Alleys	1.52 meters minimum
Driveway entrances	1.52 meters minimum
Fire hydrants	1.52 meters minimum
At-grade utilities (sewer vents)	1.52 meters minimum
At-grade utilities (water shut-offs)	1.52 meters minimum
At-grade utilities (gas shut-offs)	1.52 meters minimum
Street and alley lights	4.57 meters minimum

A.2 GIS Data Sources

GIS Data Source Table

City	Bus Routes	Street Centerlines	City Limits
Anaheim	Orange County Transportation Authority	City of Anaheim	City of Anaheim
Atlanta	Atlanta Regional Commission	Fulton County	Fulton County
Buffalo	University of Buffalo	City of Buffalo	City of Buffalo
Columbus	Central Ohio Transit Authority	City of Columbus	City of Columbus
DC	City of Washington	City of Washington	City of Washington
Denver	Regional Transportation District	City of Denver	City of Denver
Detroit	City of Detroit	City of Detroit	City of Detroit
Pittsburgh	Pittsburgh Regional Transit	City of Pittsburgh	City of Pittsburgh
Houston	Houston-Galveston Area Council	City of Houston	City of Houston
Los Angeles	City of Los Angeles	City of Los Angeles	City of Los Angeles
Madison	City of Madison	City of Madison	Wisconsin Department of Natural Resources
Minneapolis	City of Minneapolis	City of Minneapolis	City of Minneapolis
Sacramento	Sacramento Regional Transit District	Sacramento County	Sacramento County
Sioux Falls	City of Sioux Falls	City of Sioux Falls	City of Sioux Falls
St. Louis	St. Louis Metro	City of St. Louis	City of St. Louis

A.3 Signage GIS Data Sources

GIS Signage Data Source Table

City	**Signage**
Buffalo	New York State
Detroit	City of Detroit
Houston	Houston Public Works
Los Angeles	City of Los Angeles
Madison	City of Madison
Sacramento	City of Sacramento
Sioux Falls	City of Sioux Falls

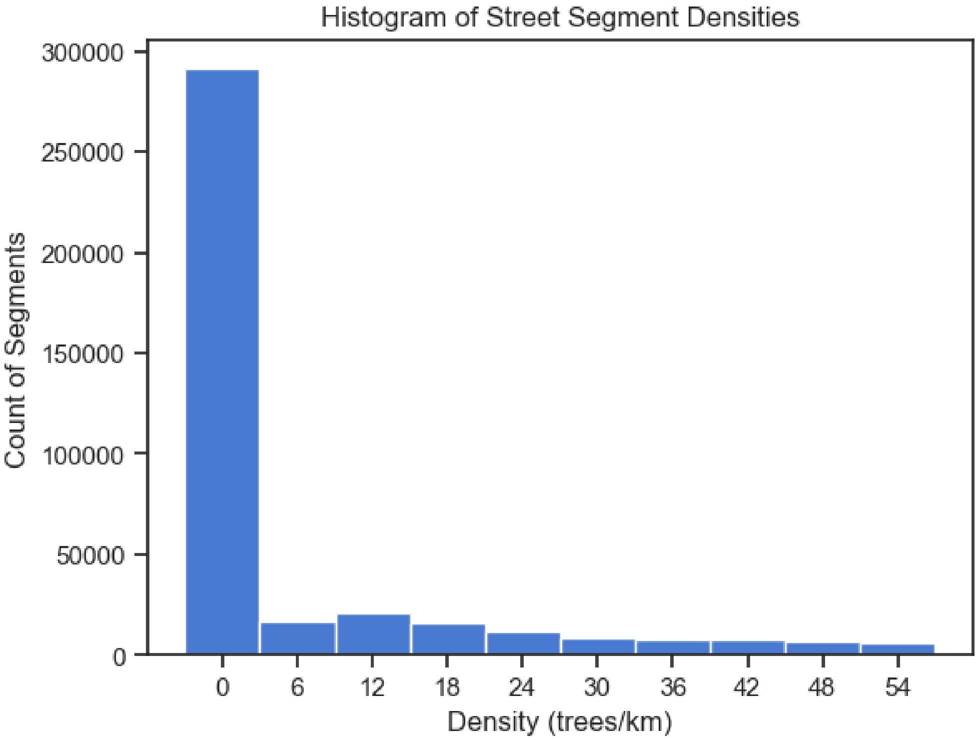

Figure A.1: Histogram of densities of street segments. The distribution is both zero-inflated and right-skewed.