EVALUATING TRANSIT EQUITY IN TODS BASED ON 5D PRINCIPLES: A SPATIAL ANALYSIS OF PORTLAND, OREGON

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EVALUATING TRANSIT EQUITY IN TODS BASED ON 5D PRINCIPLES: A SPATIAL ANALYSIS OF PORTLAND, OREGON

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LIST OF SYMBOLS AND ABBREVIATIONS

TOD	Transit-Oriented Development
TDI	Transportation Disadvantaged Index
GWR	Geographically Weighted Regression
TriMet	Tri-County Metropolitan Transportation District of Oregon
MAX	Metropolitan Area Express
WES	Westside Express Service
POI	Points of Interest
BRT	Bus Rapid Transit

SUMMARY

This thesis evaluates the impact of Transit-Oriented Development (TOD) on transit equity in Portland, Oregon, from 2020 to 2023. Using a dual-framework of horizontal and vertical equity, the study analyzes the spatial distribution of transit-supportive environments assessed by 5D Index and transportation-disadvantaged populations calculated by Transportation Disadvantaged Index (TDI). Horizontal equity is measured through Lorenz curves and Gini coefficients, while vertical equity is examined utilizing Geographically Weighted Regression (GWR). Results show modest improvements in the overall equality of TOD features and stronger alignment between TOD investments and areas exhibiting higher levels of transit equity, particularly in east Portland. However, some regions remain underserved. The study provides a replicable method for assessing TOD equity and offers guidance for planners aiming to prioritize investments that advance transportation justice.

CHAPTER 1. INTRODUCTION

Public transit has long served as a critical mode of transportation for long-distance commuting, particularly among population groups with limited access to private vehicles. For minority communities, low-income households, and other transportation-disadvantaged groups, public transit remains not just an alternative, but often a necessity for accessing employment, education, healthcare, and other essential opportunities. However, disparities in the distribution and quality of transit service across urban regions have raised pressing concerns about the equity of public transportation systems.

In recent decades, many North American cities have faced intersecting challenges including concentrated urban poverty, increasing suburbanization, and rising car dependency. These structural shifts have often resulted in growing spatial mismatches between affordable housing and job locations, disproportionately impacting residents who rely on public transit. As a response to these challenges, transit-oriented development (TOD) has emerged as a prominent planning strategy to promote sustainable, accessible, and equitable urban growth.

TOD is commonly defined as a high-density, mixed-use area—typically composed of residential and commercial land uses—within easy walking distance (approximately 800 meters) of a high-capacity transit station (Galelo et al., 2014). The intention behind TOD is to encourage public transit usage, reduce automobile dependence, and improve access to opportunities through strategic land use. When designed effectively, TODs can foster compact, walkable, and connected communities. However, growing empirical research has also documented the potential unintended consequences of TOD, particularly its

association with gentrification and displacement. As housing prices and property taxes rise around newly developed transit corridors, historically marginalized residents may find themselves priced out of the very neighborhoods that TOD was meant to serve (Xu et al., 2016; Zhao et al., 2024).

Given these dynamics, there is an urgent need to evaluate the extent to which TOD initiatives genuinely promote transportation equity. This thesis aims to develop a comprehensive and spatially sensitive methodology to assess how TOD programs affect transit equity, with a particular focus on disadvantaged populations. Using the Portland metropolitan region in Oregon as a case study, this research applies a consistent framework of spatial data and analytical techniques to evaluate the relative quality of transit service to employment opportunities before and after TOD interventions. Specifically, the study integrates measures such as the Transportation Disadvantaged Index (TDI), the 5D built environment index, Lorenz curves, Gini coefficients, and Geographically Weighted Regression (GWR) to quantify both horizontal and vertical equity outcomes across different time periods.

The overarching objective of this thesis is to support the identification, evaluation, and quantification of transit equity impacts associated with TOD. To that end, the following chapters review the theoretical and empirical literature on transport equity, introduce the analytical framework, and present the findings of a detailed spatial equity assessment of TOD-affected areas. In doing so, this research contributes to a deeper understanding of the role TOD can play in advancing—or potentially hindering—transportation justice in contemporary urban contexts.

CHAPTER 2. LITERATURE REVIEW

2.1 Transit Service Equity

Public transit plays a vital role in enhancing transportation equity, particularly by expanding mobility options for disadvantaged populations and increasing access to employment, services, and social opportunities. Transit services are often viewed as a public good that can mitigate structural barriers faced by marginalized groups, thus advancing broader societal goals such as social inclusion and environmental justice.

2.1.1 Theoretical Framework of Equity in Transportation

In the field of geography and transportation planning, equity has long served as a conceptual framework to evaluate the spatial distribution of opportunities and services (Keeble et al., 1982; Truelove, 1993). Equity, broadly defined, encompasses justice, integrity, and fairness across social, philosophical, and technical contexts. In transportation equity literature, the concept is commonly distinguished into two primary forms: horizontal equity and vertical equity (Litman, 2007). Horizontal equity refers to the fair treatment of individuals or groups considered equal in terms of ability and need. This perspective emphasizes uniform access to transportation services and avoids preferential treatment.

Vertical equity, in contrast, acknowledges differences in social and economic status and advocates for preferential treatment to address structural disadvantages. This includes prioritizing services for those with fewer resources or greater needs, such as low-income populations, people with disabilities, and the elderly. Hwang et al. (2024) examined the potential impact of the On-Demand Multimodal Transit System (ODMTS) on both

horizontal and vertical transit equity analysis compared with the existing transit system, providing methodological inspiration for this thesis through their use of a similar analytical framework, incorporating both horizontal and vertical equity analysis before and after the implementation.

2.1.2 Horizontal Equity and Transit Supply Distribution

A substantial body of literature focuses on measuring horizontal equity by evaluating the spatial and quantitative distribution of transit services. Analytical tools such as Lorenz curves and the Gini coefficient are frequently employed to assess whether transit supply is equitably distributed among the population.

For example, Delbosc and Currie (2011) used Lorenz curves to examine the spatial equity of public transportation in Melbourne, accounting for both frequency and walking distance to transit stops. Similarly, Welch and Mishra (2013) developed a graph-based methodology to assess the spatial structure and connectivity of public transit systems. Their connectivity index considered both physical infrastructure and service attributes to evaluate supply distribution. Other studies have highlighted spatial disparities in transit provision through GIS-based mapping and spatial clustering analyses (Delmelle and Casas, 2012).

These studies underscore how inequitable transit supply can reinforce existing social inequalities when transit resources are unevenly distributed across space.

2.1.3 Vertical Equity and the Needs-Based Approach

In contrast to horizontal equity, vertical equity emphasizes the redistribution of resources to meet the needs of socially disadvantaged groups. This includes prioritizing

transit access for individuals without private vehicles, low-income households, racial or ethnic minorities, the elderly, and people with disabilities (Garrett & Taylor, 1999; Murray & Davis, 2001; Deakin, 2007; Ward, 2005).

The needs-based approach is commonly adopted in vertical equity analysis. Murray and Davis (2001) proposed a transport need index based on indicators such as household income, unemployment rate, and household size, and compared this index with the spatial coverage of public transit. Currie (2010) expanded this framework by developing a public transport supply index incorporating service frequency, quality, and spatial coverage, followed by a gap analysis comparing need and supply across regions. Delbosc and Currie (2011) further examined vertical equity by evaluating how transit supply corresponded to the distribution of vulnerable demographic groups such as older adults and households without cars.

Additionally, Wu and Hine (2003) introduced the Public Transport Accessibility Level (PTAL) approach, which combines measures such as walk time to transit, waiting time, frequency, and service reliability into a composite score reflecting accessibility from a vertical equity perspective.

2.1.4 Evidence of Inequity in Transit Access

Numerous empirical studies have highlighted the disproportionate burden faced by disadvantaged groups in accessing transportation. According to The Leadership Conference Education Fund (2011), low-income individuals, rural residents, elderly populations, and persons with disabilities often encounter substantial mobility barriers. These groups are more likely to live in auto-dependent environments, face higher relative

transportation costs, and experience reduced access to employment and social services (Litman, 2002; Lucas & Jones, 2012).

Lucas and Jones (2012) emphasized the role of transportation systems in alleviating social exclusion, arguing that improved transit access for vulnerable populations contributes to overall societal equity. Public transportation systems, therefore, are not just a means of mobility but also a mechanism for achieving broader social objectives.

2.2 Measurement of Transit Service

The evaluation of transit equity necessitates accurate measurement of transit supply. Two major dimensions are commonly used in literature: accessibility and connectivity. The integration of TOD with transit equity frameworks also offers promising pathways for urban development.

2.2.1 Accessibility Measures

Accessibility refers to the ease with which individuals can reach desired destinations using the transportation system (Morris et al., 1979; Vandenbulcke et al., 2009). Handy and Niemeier (1997) categorized accessibility measures into: cumulative opportunity measures, which count the number of destinations reachable within a given travel time or distance; gravity-based measures, which assign greater weight to closer destinations based on travel impedance; and utility-based measures, which model individual travel choices and preferences. Geurs and van Wee (2004) later proposed four perspectives for measuring accessibility: infrastructure-based, location-based, person-based, and utility-based.

Most studies on transit equity adopt macro-scale, infrastructure- or location-based measures due to data availability and policy relevance. For instance, researchers frequently measure the distance from residential areas to the nearest transit stop (Handy & Niemeier, 1997) or estimate travel time from home to work using public transit (Weber, 2003). These calculations are often conducted using GIS tools (O'Sullivan et al., 2000). Kawabata (2009) notes that accessibility can vary significantly across income and racial groups, reinforcing the relevance of equity considerations in these measures.

Activity-based approaches assess access to specific opportunities such as employment or essential services. Delmelle and Casas (2012) used such measures to assess the spatial distribution of Bus Rapid Transit (BRT) systems, while Vandenbulcke et al. (2009) examined average travel times to train stations to reveal geographic disparities in transit access.

2.2.2 Connectivity Measures

Connectivity reflects how well different components of the transit system are linked. In network analysis, this is often measured through centrality metrics, which evaluate the importance of a node (e.g., a station) based on its connection to other nodes or routes (Borgatti, 2005; Yang et al., 2007).

Hadas and Avishai (2010) introduced a performance index that includes not only connectivity but also service frequency, demand, and transfer comfort. Welch and Mishra (2013) developed a composite connectivity index that incorporates travel speed, distance, service frequency, required transfers, and the land-use density surrounding transit stops. These enhanced indices help reveal whether well-connected transit nodes also serve areas

with high population or employment density—key factors in both horizontal and vertical equity assessments.

2.2.3 TOD Measures

Transit-oriented development (TOD) is an urban planning approach that aims to create sustainable and equitable communities by constructing high-density mixed-use developments around rail stations (Wan and Lu, 2023). Cervero and Kockelman (1997) investigated how the 3Ds (Density, Design, and Diversity) influence the trip rates and mode-choice of residents in the San Francisco Bay area. In this study they tried to find out the influence of these 3D principles on travel demand. Huang et al. (2021) have concentrated in a study on performance of TOD nodes by evaluating their individual TOD level and how they are performing in TOD network. In this study, they have developed a TOD typology, based on built-form indicators (5Ds) to identify the roles of diverse types of nodes within the transit network. This research was used to determine how each node in distinct typologies complements each other to strengthen the network's properties. Finally, they discovered that different sorts of nodes in the network have distinct effects. As a result, they advise planning and evaluating TOD as a network.

Kamruzzaman et al. (2014) have explored the built environment indicators such as density, diversity, design, distance to transit, and destination accessibility and developed a typology that is taken as basis for analysis in Brisbane, Australia. Local government wanted to develop 6 types of TODs in Brisbane but city structure was able to possess only 4 types of neighborhood developments. This paper assessess how 5D principles help in developing a typology that will be used to develop the city. Similarly, Islam et al. (2021) identified the

built-form indicators and BRTS ridership in Ahmadabad region. GIS was used to determine built-form indicators such as “density, diversity, design, destination accessibility, and distance to transit station by creating buffer zones surrounding each station”. Regression analysis is done to understand the ridership factors. Because of its ability to deal with primary factors, the regression method was used.

By aligning built-environment characteristics with transit accessibility and demographic needs, TOD planning can address both horizontal equity and vertical equity. When evaluated as a spatial network using the 5D framework or node typologies, TOD strategies can be refined to serve both system performance and social equity goals.

CHAPTER 3. DATA AND ANALYSIS

3.1 Study Area

The study area encompassed all block groups in Portland, Oregon, focusing on those hosting TOD programs. Portland, the largest city in Oregon, is situated in the Pacific Northwest region of the United States, at the confluence of the Willamette and Columbia Rivers. Portland's metropolitan region is served by a coordinated network of transportation agencies that manage planning, operations, and funding of its transit system. The primary regional agency, Tri-County Metropolitan Transportation District of Oregon (TriMet), operates the majority of public transit services within the study area (shown in Figure 1), including Metropolitan Area Express (MAX) light rail, bus, and Westside Express Service (WES) commute rail. As of 2025, TriMet's system includes 5 MAX light rail lines with a total route length of approximately 60 miles and 94 stations, providing over 21 million annual rides. TriMet also operates bus network that comprises 6,153 stops across 79 routes. WES, operated by Portland & Western Railroad (P&W), is a commuter rail line serving parts of the Portland metropolitan area. It serves five stations and travels 14.7 miles between Beaverton and Wilsonville. delivering roughly 6 million annual rides.

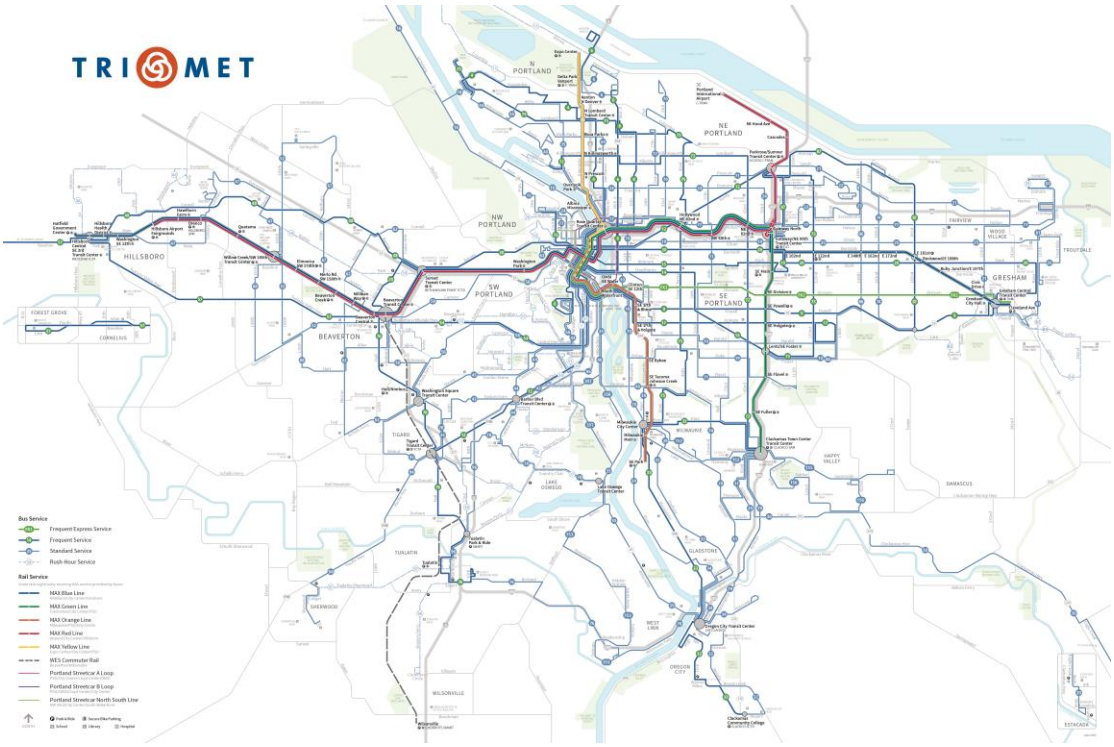

Figure 1 - Transit Network in Portland, Oregon

In parallel, Metro—Portland's regional government—oversees long-range land use and transportation planning, including the allocation of federal transportation funds and the implementation of TOD strategies. In its pursuit of sustainable and equitable urban growth, Portland has been investing in packages that expand accessible transportation networks and increase the availability of affordable housing, with TOD serving as a key component. Metro's TOD initiatives support equitable development and healthy communities along the city's transit corridors. According to the report of Metro's TOD program accomplishments, the projects not only create places for people to live and work near high-quality, low-cost transit, but also enhance the compact development of commercial spaces and affordable housing units. These features make Portland an ideal case for studying the impacts of TOD on transit equity.

3.2 Transit Equity Metrics

3.2.1 Transportation Disadvantaged Index (TDI)

As vertical equity emphasizes the importance of fairness based on different levels of needs, asserting that transportation resources should be distributed disproportionally toward populations with greater barriers to access travel options (Lucas, 2012; Martens, 2016), the TDI was created to quantify the concentration of vulnerable populations at the block group level, especially in aspects of travelling. In line with U.S. Department of Transportation guidance and previous academic literature (Karner et al., 2020; Grengs, 2015), we selected the following six demographical variables: 1) Elderly population (age above 65), 2) Children and youth (age under 15), 3) Households without a vehicle, 4) Population below the federal poverty line, 5) Population with disabilities, 6) Population with limited English proficiency. To compare transit service and equity, data from both before and after the completion of the targeted TOD programs were collected. All variables were sourced from U.S. Census 2020 and 2023 ACS 5-year estimates. To ensure each component contributes equally to the index regardless of its original scale, each was transformed into a standardized z-score, using the following formula (1):

$$z = \frac{x - \mu}{\sigma} \tag{1}$$

where x is the original value, μ is the mean, and σ is the standard deviation of that variable across all block groups.

The final TDI was constructed by aggregating six standardized components with equal weighting. This resulted in a continuous index where higher values represent a greater concentration of transportation-disadvantaged populations.

3.2.2 5D Index

To determine the metric we use to evaluate the improvements on transit services that TOD brings, we not only considered the accessibility, but also the transportation services provision including availability of low-cost transit options, frequency of services, and alleviation of specific barriers to access. To quantify those metrics, we appoint an index developed from 5D framework. The 5D framework that incorporates Density, Diversity, Design, Destination accessibility, and Distance to transit, developed from the 3D framework by Cervero and Kockelman (1997), provides a holistic view of the built environment, transit service and their relationship. Each dimension offers a distinct yet interrelated aspect of evaluation:

- Density captures population and job concentration.
- Diversity reflects land use mix and economic inclusivity.
- Design measures quality of service each station provides.
- Destination Accessibility assesses access to key services.
- Distance to Transit evaluates how close people live to transit services.

These are established factors that could influence travel behavior and accessibility, and thus provide a justifiable basis for evaluating whether TOD projects have been located where they are most needed. Numerous studies, as mentioned in the literature review, demonstrate that the 5D variables correlate with more equitable distribution of transit

services. By incorporating both spatial and socio-spatial dimensions, the 5D framework bridges gaps left by accessibility-only or user-experience-only models.

Specifically, the measurement methods and data source for each factor are elaborated in Table 1. In this study, we used the cumulative opportunities measure to assess transit accessibility, which counts the number of Points of Interest (POI) visits accessible within a certain threshold. This approach captures actual behavior rather than modelled potential, allowing insight into how often residents of different areas engage with urban services and opportunities via transit-accessible destinations. While not explicitly tied to transit schedules or infrastructure, the spatial pattern of POI visits provides a strong behavioral proxy for accessibility outcomes among marginalized communities. According to Calthorpe, a TOD area should be "a mixed-use community within an average 10-minute walking distance of a transit stop and core commercial area. Therefore, transit accessibility in Portland, Oregon is empirically assessed using visit frequency to POIs within 10-minute walking distance. The data source is the Advan Research Monthly Patterns dataset from Dewey Data, which provides aggregated location-based visitation information.

Table 1 - Data Description of Factors Composing 5D Index.

Factor	Indicator	Indicator Description	Data Source
Density	Population density	Resident population density in the block group	Census
	Employment density	Employment density in the block group	Census
Diversity	Entropy score	Shannon's Entropy Index (H)	ODOT TransGIS

Table 1 Continue

Design	Transit frequency	The frequency of transit arrivals at each stop	TriMet GTFS
	Affordability	The fare of each stop	TriMet GTFS
	ADA Accessibility	Whether the station is accessible for ADA	TriMet GTFS
Destination Accessibility	Accessibility of the transit station	Poi visits originated from disadvantaged block groups	Dewey Data
Distance	Distance to transit	The distance from the centroid of each block group to the nearest transit stop	TriMet GTFS

In addition to accessibility, land use mix within each block group was quantified using an entropy score. Entropy reflects the degree of land use diversity, with higher values indicating a more balanced mix of residential, commercial, and institutional uses, thereby indicating higher diversity. The entropy index was computed using the standard formula (2):

$$H = -\sum_{i=1}^{n} P_i ln P_i \quad (2)$$

where: P_i is the proportion of land use type, i in the area. n is the number of land use types.

3.3 Conceptual Framework

Transit equity is a multidimensional concept. In this study, equity is examined through two complementary lenses—horizontal equity and vertical equity. The result of both measures provides a holistic assessment of how TOD policies in Portland have impacted multifarious populations in terms of transportation access and opportunity

3.3.1 Horizontal Equity (Equality)

Horizontal equity refers to the principle that individuals or groups with similar needs and circumstances should be treated equally. In the context of transportation, this means equal access to mobility resources such as transit service coverage, frequency, and accessibility regardless of location or social status (Litman, 2007). This dimension is critical for evaluating fairness tradeoffs in TOD, as an equitable transit system should not only increase overall accessibility but also ensure that the advanced services are not concentrated in already well-served areas.

To measure these disparities, this study employs the Lorenz curve and Gini coefficient, two standard tools in inequality research (Sen, 1973; Delbosc and Currie, 2011). These tools visualize and quantify the distribution of transit accessibility across all block groups in Portland, comparing the pre- and post-TOD contexts to assess whether accessibility became more evenly distributed as a result of the interventions. The Lorenz curve is a graphic representation of the Gini coefficient with the 45-degree line representing a perfectly equitable distribution. The area between that line and the Lorenz curve indicates the overall degree of inequality. The more Lorenz curve deviates from the line of equality, the more inequal is the transit resource allocation in the study area.

To quantify the extent of this inequality, the Gini coefficient was calculated from the area between the Lorenz curve and the line of equality. The Gini coefficient ranges from 0 to 1, whereas a Gini value of 0 indicates perfect equality and a Gini value closer to 1 indicates high inequality in the distribution. Mathematically, the Gini coefficient (G) is computed in formula (3).

$$G = 1 - \sum_{i=1}^{n} (Y_i + Y_{i-1})(X_i - X_{i-1}) \quad (3)$$

Where X_i and Y_i represent the cumulative proportions of the population and 5D index respectively, and n is the number of populations. The results are compared before and after the implementation of TOD programs. This approach enables clear visualization and measurement of changes in transit service equity over time, thereby revealing whether TOD interventions have led to more equitable outcomes across the urban landscape.

3.3.2 Vertical Equity (Equity)

Vertical equity, on the other hand, acknowledges that some populations face disadvantages and barriers that limit their mobility options. It promotes an allocative principle: those with greater need should receive proportionally greater transportation support (Lucas, 2012; Martens, 2016). In this study, vertical equity is measured through the spatial analysis of interrelationship of TDI and 5D Index we created before, as BGs with high TDI represent groups experiencing multiple obstacles to accessing high-quality transit, including affordability, information access, physical mobility, and safety (Karner et al., 2020).

By regressing the 5D Index against the TDI using a GWR model, the study examines how well the spatial distribution of transit-supportive environments aligns with disadvantaged population clusters. This spatially explicit approach provides insight into whether TOD accomplishments have improved conditions in areas in higher need. By estimating location-specific coefficients, GWR enables a holistic analysis of how the strength and direction of the relationship between TDI and 5D vary across space, thereby

identifying where TOD programs are most effective and where gaps in service equity remain.

3.3.3 Integration of Equality and Equity

This conceptual framework allows for a multifaced understanding of TOD performance that not only estimates whether accessibility has improved overall, but also tests whether these improvements have mitigated disparities and enhanced access for transportation underserved populations. This dual framework fills out the gap in TOD literature that often prioritize aggregate accessibility improvements without regard to who benefits.

However, several methodological limitations are inevitable. Firstly, the TDI was constructed by aggregating six standardized components with equal weights, assuming uniform contribution from each factor despite potential differences in their impact. Similarly, the 5D index was derived from spatial indicators that may introduce inaccuracies when comparing pre- and post-TOD conditions, as some built environment factors may not precisely align with the specific year of analysis. Besides, GWR model relies on assumptions regarding bandwidth selection, spatial independence, and model stationarity. Furthermore, the temporal demarcation of TOD project implementation may not fully capture the lagged or gradual impacts of such interventions. These limitations suggest that while the findings offer vital insights into spatial analysis of transit equity, they should be interpreted with caution and supplemented with future research using more dynamic and up-to-date data.

CHAPTER 4. RESULTS

4.1 Impact of TOD programs on TDI and 5D Index

Figures 2 and 3 show the spatial distribution of the 5D Index in 2020 and 2023, respectively. In 2020, the 5D index was highest in downtown Portland, highlighting its strong support for equitable, multimodal, and transit-oriented mobility. Meanwhile, the distribution is concentrated in a limited number of block groups, primarily located along established transit corridors in central, southeast Portland and near the Portland International Airport. Large areas in southwest, middle north, and northwest Portland had relatively low 5D scores, indicating a lack of TOD-supportive built environment.

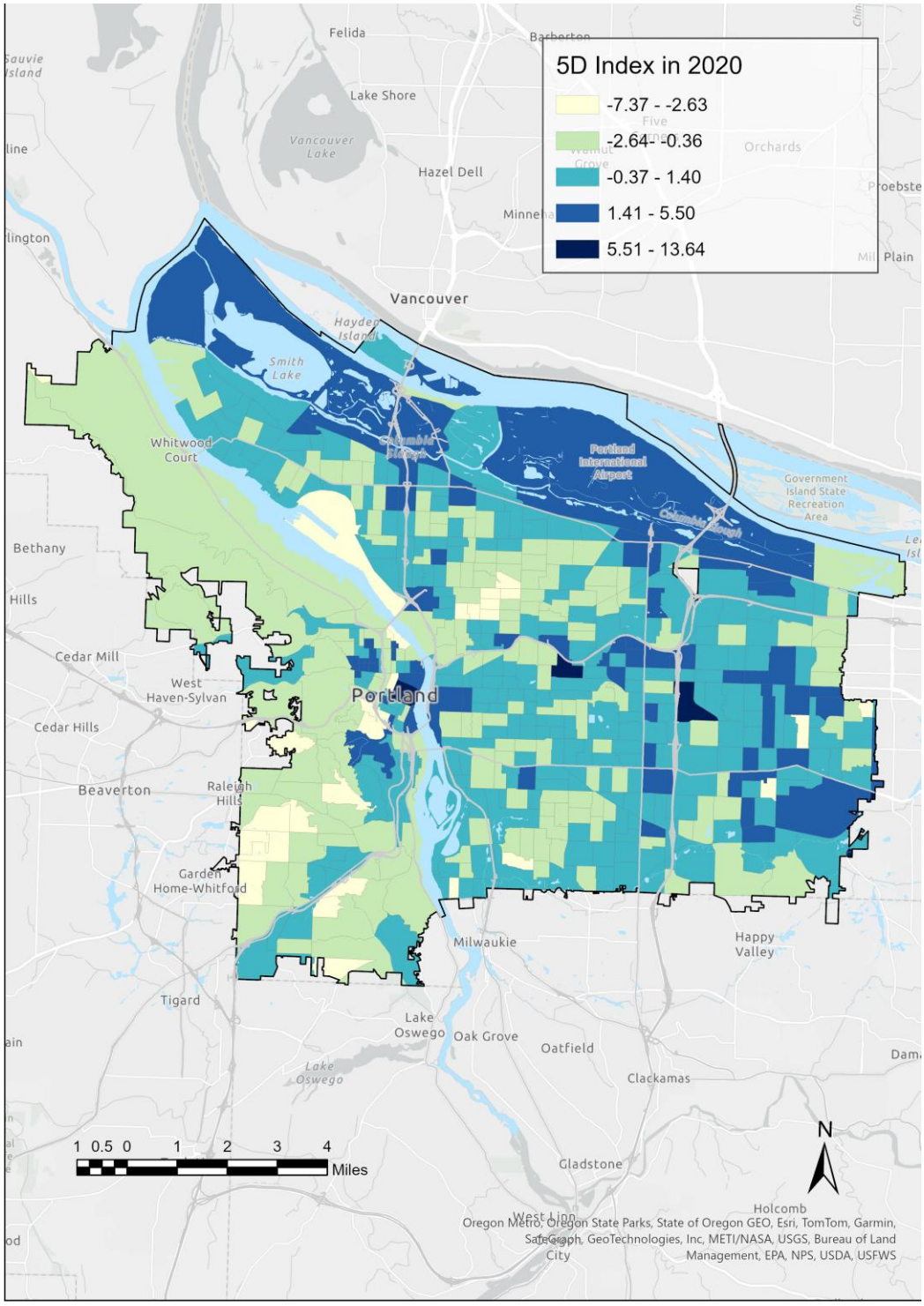

Figure 2 - Distribution of 5D Index in 2020

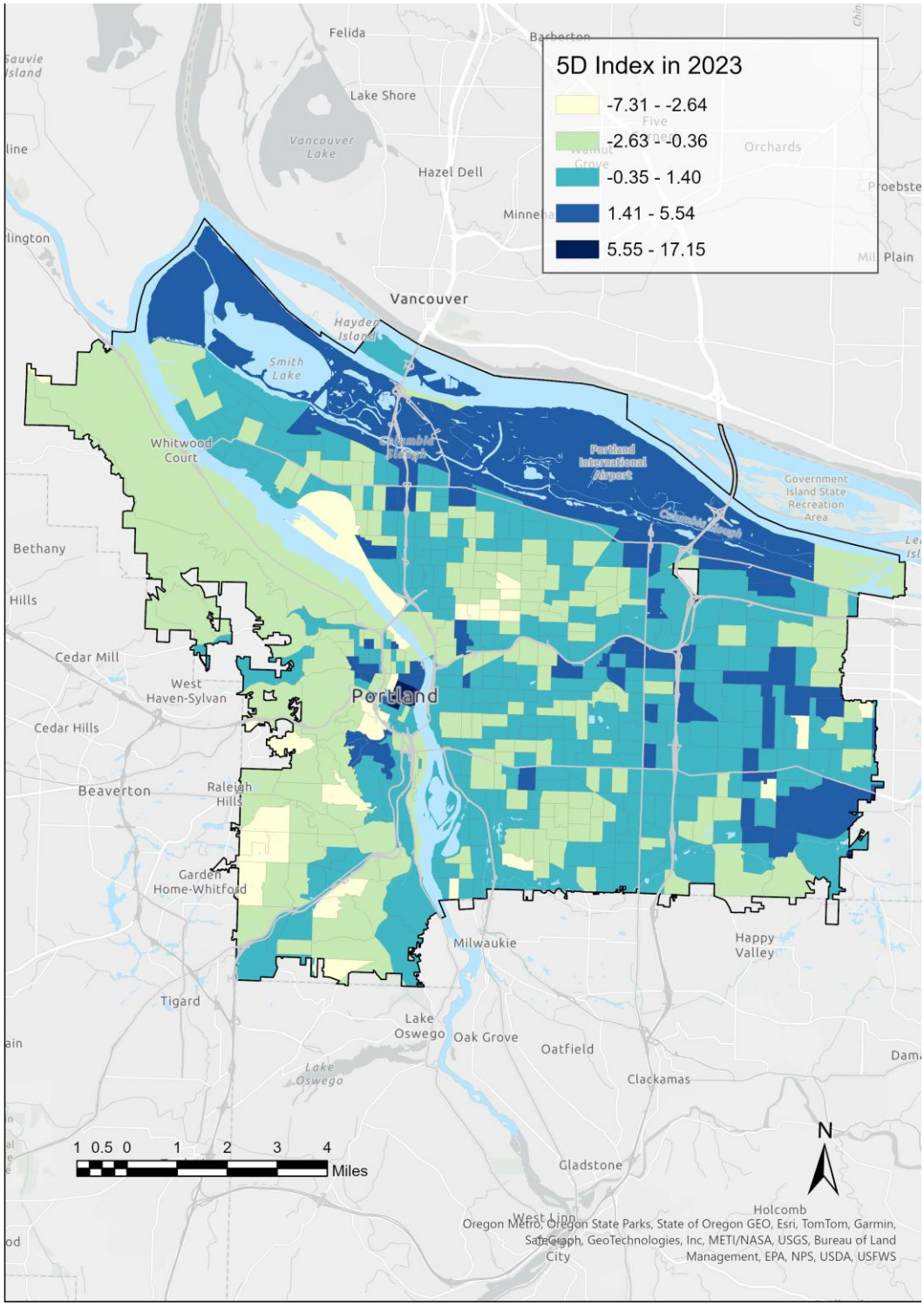

Figure 3 - Distribution of 5D Index in 2023

By 2023, the 5D Index distribution shows a slight upward shift in overall intensity and spatial coverage. A greater number of block groups exhibit mid-to-high index values, especially in the eastern parts of the city. The improved accessibility and increased density along these corridors resulted from investments in bus rapid transit system and TOD initiatives likely contributed to higher 5D scores. This shift supports the hypothesis that TOD programs enhanced the quality of the transit-oriented built environment across a broader geographic area, rather than concentrating improvements exclusively in downtown areas. However, whether the areas that have been improved are those with the greatest need for transit remains to be examined in the following sections.

Figures 4 and 5 present the distribution of the TDI in 2020 and 2023. In 2020, high TDI values, which represent the block groups with higher concentration of disadvantaged groups, were predominantly concentrated in east and southwest Portland, such as the Lents, Hazelwood, and Powellhurst-Gilbert neighborhoods, as well as parts of north Portland including BGs around Smith Lake. These areas are known for hosting a larger proportion of low-income households, elderly residents, non-English speakers, and zero-vehicle households.

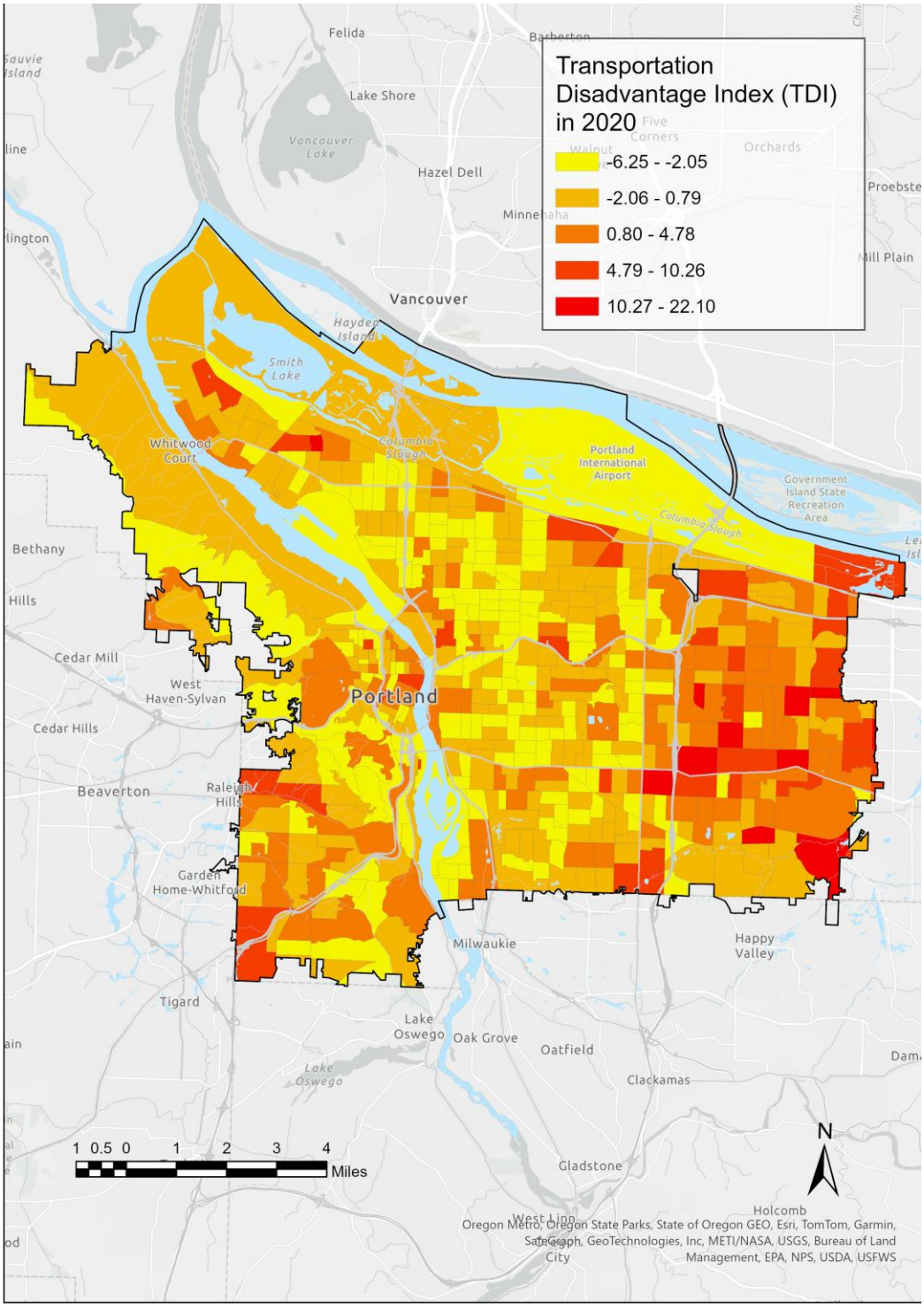

Figure 4 - Distribution of TDI in 2020

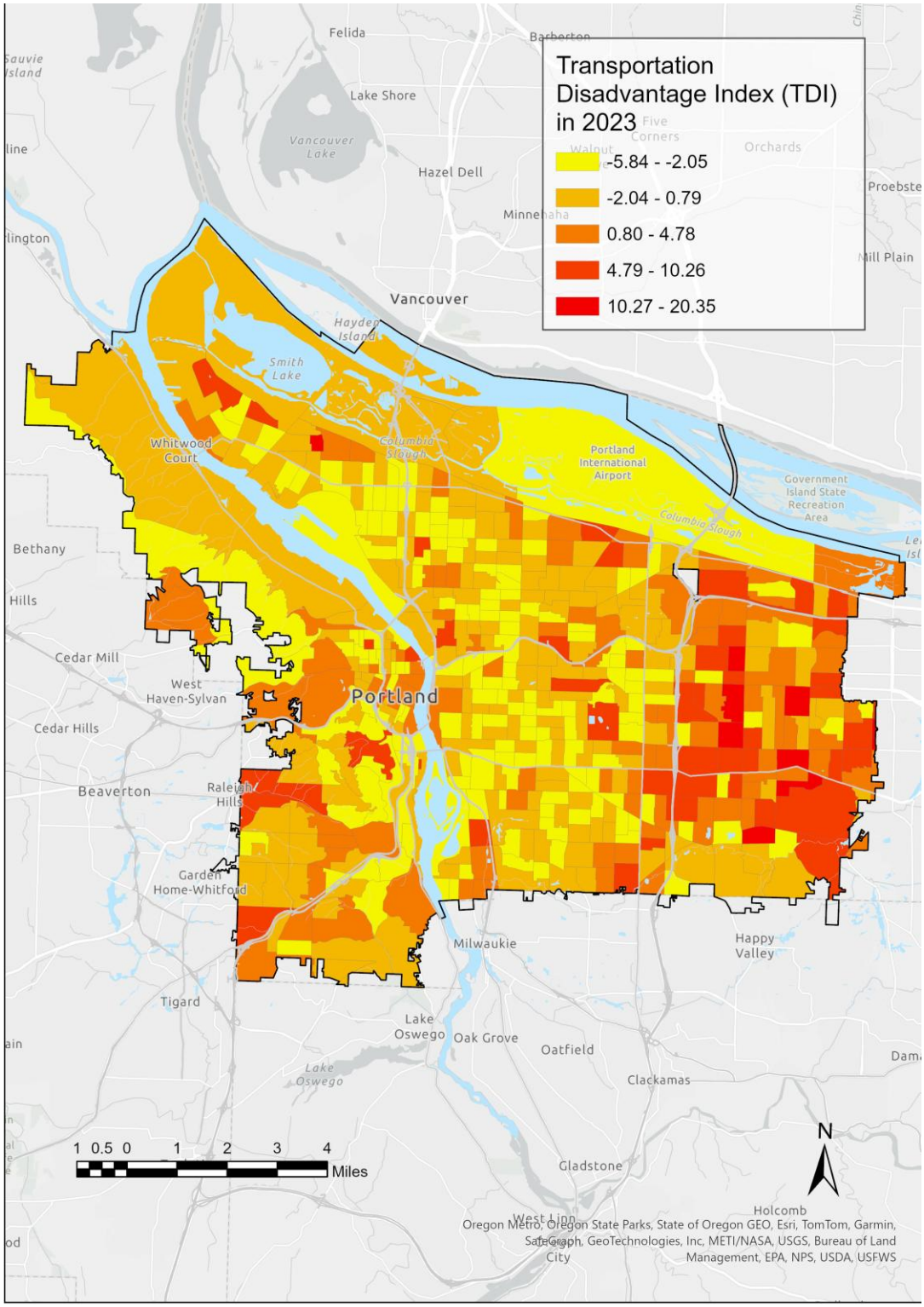

Figure 5 - Distribution of TDI in 2023

In 2023, the spatial pattern of TDI remains relatively stable, indicating persistent concentrations of transportation-disadvantaged populations in the same neighborhoods. However, the overall TDI scores have decreased slightly, which could probably be attributed to demographic shifts or socioeconomic improvements over the past three years. Importantly, there is little evidence of dramatic change in the core areas of high disadvantage, emphasizing the need for long-term targeted TOD programs, particularly in areas where vulnerable populations remain clustered.

The distributional shift in TDI toward lower scores suggests a decline in the presence of transportation-disadvantaged populations within the city, potentially due to demographic displacement linked to development pressure. Meanwhile, the modest upward shift in the 5D index distribution indicates that TOD investments enhanced transit-supportive urban form in more areas. These contrasting patterns highlight a tension between improving the built environment and maintaining equitable access for vulnerable populations.

4.2 Impact of TOD programs on Horizontal Equity

Figure 6 illustrates a Lorenz curve of 5D Index distribution among BGs in 2020 and 2023. As shown in the graph, both years exhibit relatively low Gini coefficients, indicating a modest level of inequality in the spatial distribution of transit-supportive environments and the accessibility they provide. In 2020, the Gini coefficient was 0.125, while in 2025, it slightly declined to 0.119. This trivial decrease suggests a subtle improvement in the equality of 5D Index values across the city, meaning that TOD-supportive features became slightly more evenly distributed over time. This trend aligns with the ongoing TOD

initiatives implemented by Metro and associated agencies during the study period, which aimed to expand access to dense, diverse, and transit-friendly environments across a broader range of neighborhoods.

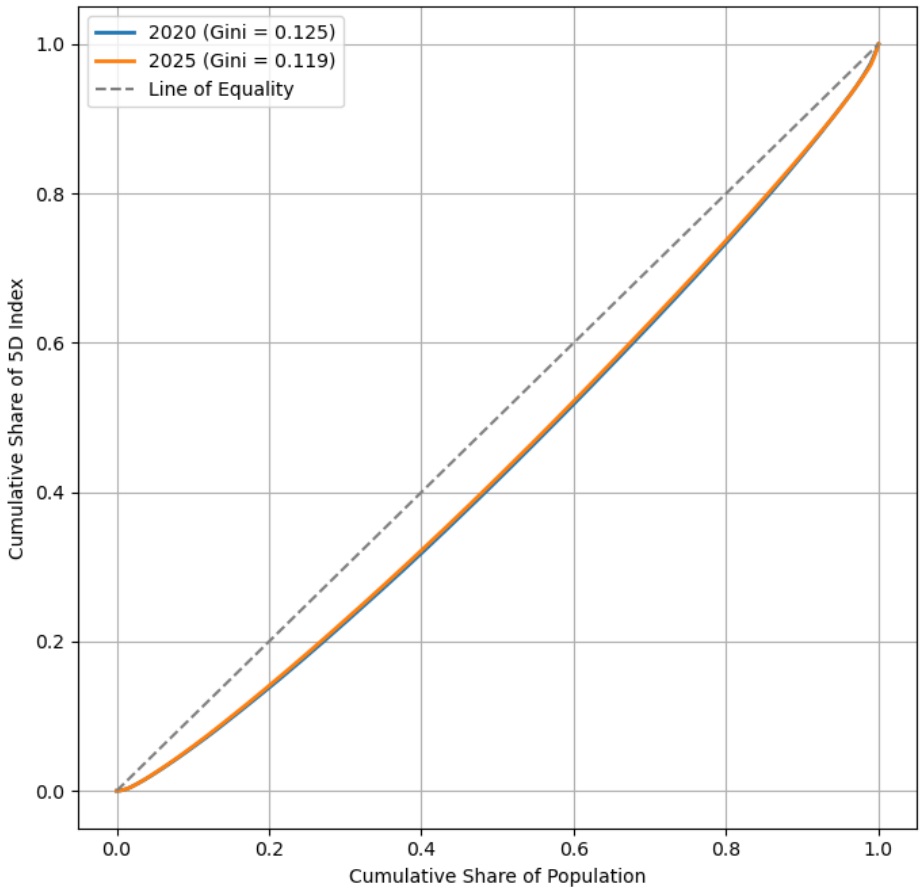

Figure 6 - Lorenz Curve for 5D Index in 2020 and 2023

While the direction of change is consistent with ongoing policy efforts to promote more inclusive urban development through TOD programs, the magnitude of change remains trivial. Two primary factors may explain this: first, the 5D Index incorporates structural and spatial characteristics of the built environment such as land use diversity, transit station design, and residential density that tend to remain stable in the short term. Unlike accessibility that changes with travel behavior and demographical transition,

transformations in infrastructure, land use regulation, and development patterns often require long-term planning horizons and are subject to various constraints from external factors. In this case, a three-year interval may be insufficient to generate substantive shifts. Second, the Gini coefficient in 2020 was already relatively low, indicating a relatively high level of equality at the beginning of the analysis. This leaves limited room for significant statistical improvement, as much of the disparity may have already been addressed in earlier phases of TOD planning. In general, Portland city demonstrates a high level of equality both before and after the implementation of the targeted TOD programs. Further analysis is required to determine whether these improvements reached the areas of greatest need, which is addressed in the vertical equity analysis section.

4.3 Impact of TOD programs on Vertical Equity

As shown in Figure 7, the GWR coefficients in 2020 vary considerably across the city, with values ranging from approximately 0.30 to 1.04. The strongest positive relationships of two indexes are found in southeastern and northwestern Portland. These areas reflect some spatial alignment between transit-supportive development and disadvantaged populations, though these relationships are geographically limited. In contrast, large portions of central and southwest Portland display lower coefficients, suggesting a weak or negligible relationship between TOD performance and transportation disadvantages in 2020. This mismatch indicates that TOD efforts had not yet been systematically aligned with social vulnerability patterns during that time.

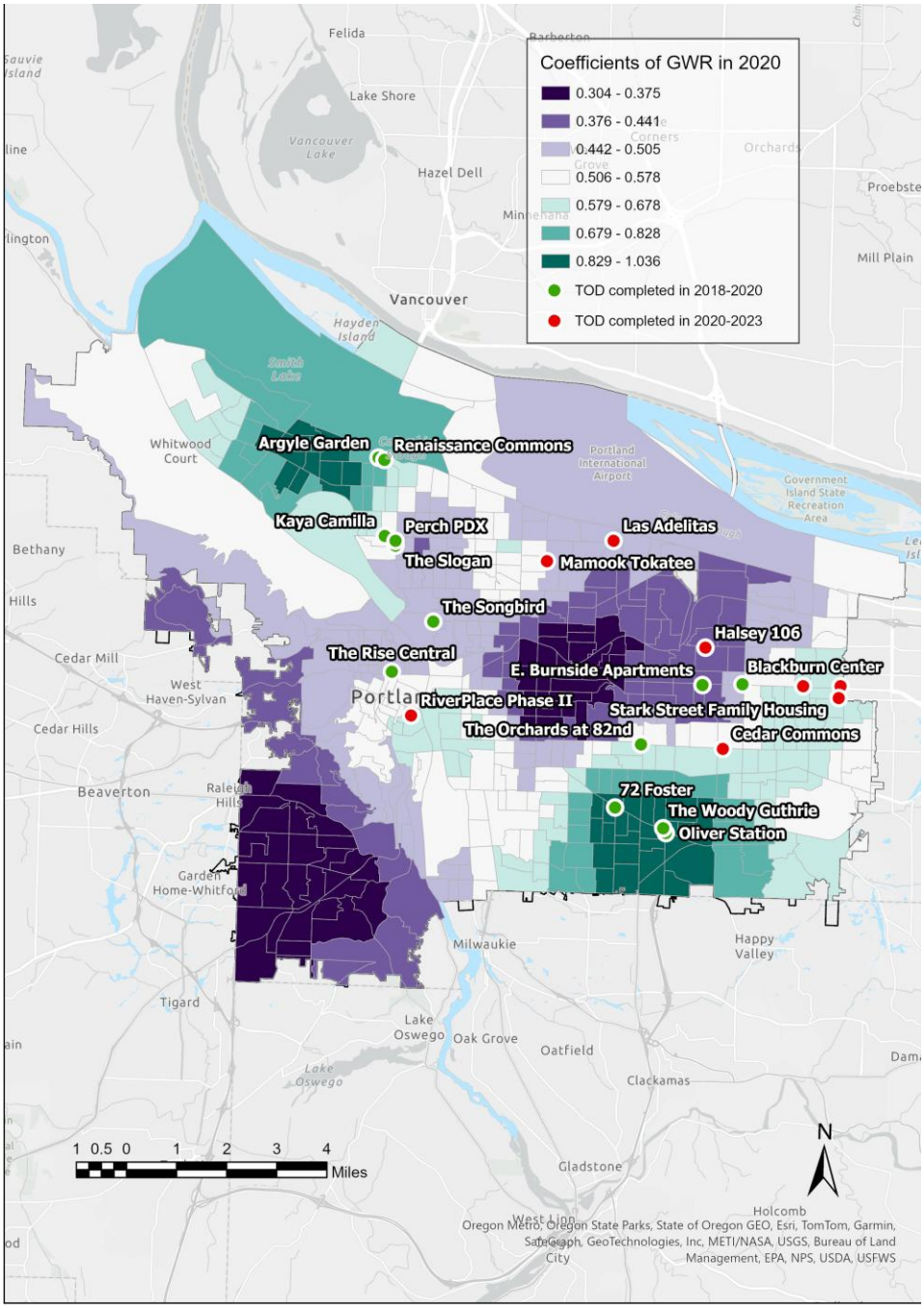

Figure 7 - Distribution of Coefficients of GWR in 2020

Notably, several TOD projects completed between 2018–2020 are clustered in areas with moderate to high GWR coefficients, such as The Woody Guthrie, Oliver Station, 72 Forster in south and Argyle Garden, Renaissance Commons in north. The spatial

correspondence suggests that the implementation of TOD initiatives in the preceding years may have contributed to strengthening the spatial association between transit-supportive built environments and disadvantaged populations. These findings imply that TOD programs and policy interventions during this period may have played a role in reinforcing vertical equity by improving conditions in locations where the alignment between need and opportunity was most responsive to intervention.

While the 2020 results offer initial evidence of the temporal evolution of TOD effectiveness in promoting transit equity, the 2023 GWR results and how they evolve from 2020 would provide empirical longitudinal evidence and strengthen the causal inference that TOD programs are effective tools for enhancing vertical equity.

Figure 8 illustrates the GWR coefficients in 2023, revealing a more pronounced spatial differentiation compared to 2020. The range of coefficients broadens (approximately 0.23 to 1.19), and stronger positive associations between TDI and 5D Index emerge in several additional neighborhoods, particularly across inner north-central corridor and outer east Portland. A key observation is that many TOD projects completed between 2020–2023 (e.g., Cedar Commons, Stark Street Family Housing, Burnside Boardwalk, and Bria Apartments) are now located in areas that demonstrate higher local coefficients, indicating an improving relationship between need and investment. These findings provide stronger evidence of TOD's role in actively shaping equity outcomes over time. It further validates the use of tools like the TDI and 5D Index in guiding investment decisions that promote vertical equity. In contrast, regions in the southwest and northwest quadrants of the city still exhibit low coefficients, suggesting continued spatial mismatch in those areas. Additionally, central Portland areas such as downtown maintain modest to low GWR

coefficients, likely due to gentrification reducing concentrations of transportation-disadvantaged populations despite high TOD-supportiveness.

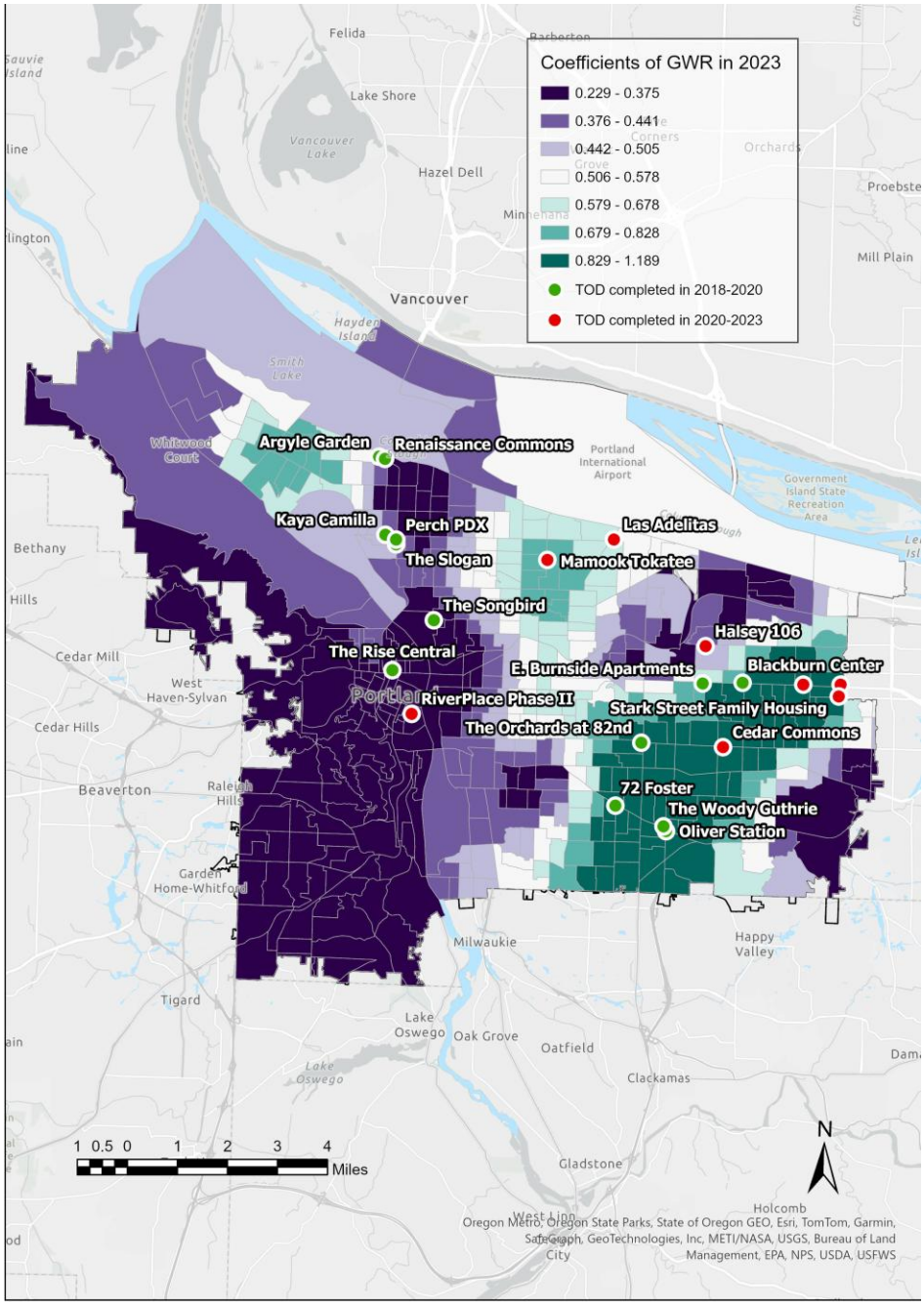

Figure 8 - Distribution of Coefficients of GWR in 20203

CHAPTER 5. DISCUSSION

This study evaluated transit equity in Portland, Oregon by combining assessments of horizontal and vertical equity before and after the implementation of key TOD programs. The integration of Lorenz curve analysis, Gini coefficient, and GWR provided a comprehensive picture of how equitably TOD investments have been distributed equally and whether they have targeted areas of greatest need.

5.1 Takeaways from Results

The Lorenz curves and Gini coefficients derived from the distribution of the 5D Index show that horizontal equity in Portland's transit infrastructure and service has performed well from 2020 to 2023. The distribution of 5D Index, which quantifies the equality of TOD-supportiveness, remains largely stable and slightly improved, as evidenced by a small shift of the Lorenz curve closer to the line of equality and a decrease in the Gini coefficient. This suggests that TOD-related improvements such as increased transit frequency, enhanced connectivity, and higher land use diversity are not solely concentrated in downtown areas but reach a broader range of neighborhoods. The modest decline in inequality may be attributed in part to the cumulative effects of TOD implementation. However, the overall high baseline equality suggests that the spatial distribution of transit-friendly built environments had already achieved a degree of uniformity across the city by 2020. This implies that TOD projects between 2020 and 2023 were likely to reinforce existing patterns rather than radically redistributing accessibility.

However, equality in the distribution of TOD features does not inherently guarantee equity. A uniform spread of TOD benefits might still omit areas with the greatest transportation need. Thus, horizontal equity must be interpreted along with vertical equity to understand the panorama of transportation resource distribution.

The GWR analysis offered insight into vertical equity by assessing the local relationship between the TDI and the 5D Index. By 2023, concentrations of higher GWR coefficients extended to several neighborhoods, particularly in the southeast and east Portland regions where many TOD projects had been implemented during past three years. This shift suggests an improvement in vertical equity: TOD programs have become better aligned with socially vulnerable areas. Nevertheless, some TOD projects were still implemented in areas with low GWR coefficients where equity gains may have declined, particularly in central and southwest Portland where urban core is located. Given that only one TOD project was implemented in the western part of the city during this period, it appears that policy attention may have shifted away from the urban core.

5.2 Limitations

The TDI and the 5D index serve as foundational pillars of the study's equity evaluation framework. The TDI effectively captures multiple dimensions of disadvantage particularly in mobility and remains a practical measure for transit equity evaluation. However, its limitations should be acknowledged. First, the equal weighting of TDI components may obscure disproportionate burdens faced by certain subgroups. For instance, low-income people have fewer barriers than people with disabilities as they still have access to affordable travel options. Second, the TDI is temporally static within the

analysis window and does not reflect short-term demographic shifts potentially resulting from gentrification processes, which could affect equity outcomes in rapidly developing TOD districts. Similarly, the 5D index remains an objective and reasonable measure of TOD projects, but it is less sensitive to annual fluctuations and does not capture policy reforms or housing affordability dynamics that directly shape who benefits from TOD. Its relative stability in Gini coefficients also points to the need for complementary qualitative measures or policy-oriented data to capture the social impacts of TOD beyond design and structural metrics.

5.3 Policy Recommendations

The differential outcomes observed across Portland city suggest that TOD success in promoting equity depends on various factors beyond project siting. First, land use compatibility plays a crucial role. In locations where TODs are supported by mixed-use zoning and affordable housing, improvements in accessibility are more likely to benefit transit-dependent populations. If TODs are implemented without affordability safeguards, the benefits may not be guaranteed to tilt toward the populations in need. Up to now, Metro has made significant progress in amplifying TOD with affordable housing strategies including inclusionary zoning, density housing bonuses, and land trusts. Second, TOD development might be impacted by gentrification. If TODs catalyze rising land values and rents without protection for original residents, disadvantaged populations may be pushed out. The low GWR coefficients in downtown Portland may reflect such dynamics. Lastly, service design matters. Without integrating on-demand and multimodal services, TODs risk becoming isolated nodes rather than contributors to the equitable network. Thus, the

observed outcomes also call for better integration between complementary policies and transit operations.

Drawing from the findings, several policy directions emerge to strengthen the equity impact of TOD: Firstly, future TOD siting should incorporate spatial analyses of the TDI and current GWR coefficients to target neighborhoods where need is high but current accessibility remains low. Secondly, urban core should not be neglected when drawing up transportation plans. Despite relatively high service levels, downtown and inner-west Portland still exhibit low responsiveness in GWR models, and the trend appears to worsen. Planning interventions in these areas should incorporate community engagement and data-driven strategies to address latent equity concerns. Moreover, transit service should include demand-responsive and multimodal options that connect low-density areas to advanced transit services. This is particularly important in outer east and southeast Portland, where TOD are making positive inroads.

Importantly, the combination of horizontal and vertical equity analysis framework offers a replicable, data-driven method for identifying mismatches between transit investment and transportation need. This methodological framework can support planners and policymakers in targeting future TOD interventions more equitably, ensuring both equal distribution and prioritized investment in disadvantaged communities.

CHAPTER 6. CONCLUSION

This study examined the spatial equity impacts of TOD programs in Portland, Oregon, by analyzing changes in both horizontal and vertical equity from 2020 to 2023. Based on a multidimensional framework, the research deployed Lorenz curves and Gini coefficients to assess equality in the distribution of transit-supportive environments, and used GWR to evaluate how well transit accessibility and supportiveness improvements aligned with the spatial distribution of transportation-disadvantaged populations. The TDI and a 5D transit service evaluation index served as key indicators in measuring the fairness of TOD interventions.

The results indicated that the distribution of the 5D index was relatively equal across Portland in both 2020 and 2023, with only modest improvement during the study period, indicating that while TOD efforts contributed to localized enhancements in accessibility, the city's overall built environment remained largely stable in its equity profile. In contrast, GWR analysis revealed more dynamic changes in the relationship between built environment characteristics and transportation disadvantage. The spatial distribution of GWR coefficients from 2020 to 2023 strengthened in several key regions, particularly in outer east and southeast Portland, where many TOD projects were implemented during this period. This shift suggests a temporal diffusion of TOD impacts, whereby newer interventions began to influence the equity beyond the initial core areas. Nevertheless, areas in southwest and northwest Portland remain weakly aligned with equity objectives. This highlights the persistent gaps in spatial targeting and the risk of assuming that areas long be seen as developed no longer require equity-oriented planning.

These findings underscore several important implications for policy and practice. First, TOD siting should also be guided by spatial equity indicators as this research has justified the utility of criterions such as the TDI and 5D index, along with bivariate spatial analysis tools, in identifying geographic equity mismatches. Second, continued monitoring, proactive intervention, and complementary policies are necessary to ensure that the benefits of TOD are distributed equitably and do not exacerbate displacement or gentrification. Third, a more comprehensive approach taking considerations of multimodal connectivity and on-demand service is necessary. By targeting investment in high-need areas, future TOD projects can reinforce both spatial fairness and social inclusion.

This research yet has several limitations. The TDI and 5D indices may not fully capture short-term demographic shifts, informal displacement, or changes in housing affordability that occur between census updates. As part of the metrics, POI visit data may introduce external effects as it is influenced not only by accessibility but also by individual preferences, trip purposes, and economic conditions. Furthermore, the study relied on data from 2020 and 2023, which may not be sufficient to capture the full temporal impacts of TOD implementation, given the gradual nature of land use change and transit ridership behavior. Moreover, while spatial correlation through GWR shows geographic alignment, it does not establish causal relationships between TOD implementation and equity improvements.

Future research can expand on this work by applying a longitudinal design over a longer time frame to observe delayed TOD impacts, particularly in neighborhoods Metro wants to put emphasis on in the development plans. Additionally, incorporating qualitative data such as resident interviews could enrich understanding of how TOD affects the ease

of travelling for the disadvantaged populations. While Portland serves as a typical case study due to its well-developed TOD policies and public transit systems, findings may not generalize directly to cities with different traffic network patterns. Comparative studies across different metropolitan areas could also help validate the generalizability of Portland's experience and inform equitable TOD planning. Finally, to better understand the social impacts of TOD, future studies should link accessibility changes with housing market dynamics, displacement indicators, and migration patterns, allowing for a more robust assessment of whether TOD investments are benefitting existing communities without the interference of external factors.

APPENDIX A. CODE

A.1 Lorenz Curve Plotting Code

```
from simpledbf import Dbf5
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt


df = pd.read_csv('D5POP_2020.csv')


# Drop NA and get values
df = df[['DDDDD_z', 'B01001_001']].dropna()
index = df['DDDDD_z'].values
pop = df['B01001_001'].values


# === Shift index values if any are negative ===
min_val = np.min(index)
if min_val < 0:
    index = (index - min_val + 1e-6)**1


# === Sort by index (ascending) ===
sorted_idx = np.argsort(index)
index_sorted = index[sorted_idx]
pop_sorted = pop[sorted_idx]
```

```
# === Compute cumulative population and cumulative index*pop ===
cum_pop = np.cumsum(pop_sorted)
cum_pop_share = np.insert(cum_pop / cum_pop[-1], 0, 0)

index_weighted = index_sorted * pop_sorted
cum_index = np.cumsum(index_weighted)
cum_index_share = np.insert(cum_index / cum_index[-1], 0, 0)

def weighted_gini(x, w):
    # x: values (e.g., TDI), w: weights (population)
    sorted_idx = np.argsort(x)
    x_sorted = x[sorted_idx]
    w_sorted = w[sorted_idx]

    cumw = np.cumsum(w_sorted)
    cumxw = np.cumsum(x_sorted * w_sorted)
    sumw = cumw[-1]
    sumxw = cumxw[-1]

    B = np.sum(cumxw * w_sorted)
    G = 1 - 2 * B / (sumxw * sumw)
    return G

gini = weighted_gini(index, pop)
```

```
df2 = pd.read_csv('D5POP_2025.csv')

# Drop NA and get values
df2 = df2[['DDDDD', 'B01001_001']].dropna()
index2 = df2['DDDDD'].values
pop2 = df2['B01001_001'].values

# === Shift index values if any are negative ===
min_val2 = np.min(index2)
if min_val2 < 0:
    index2 = (index2 - min_val2 + 1e-6)**1

# === Sort by index (ascending) ===
sorted_idx2 = np.argsort(index2)
index_sorted2 = index2[sorted_idx2]
pop_sorted2 = pop2[sorted_idx2]

# === Compute cumulative population and cumulative index*pop ===
cum_pop2 = np.cumsum(pop_sorted2)
cum_pop_share2 = np.insert(cum_pop2 / cum_pop2[-1], 0, 0)

index_weighted2 = index_sorted2 * pop_sorted2
cum_index2 = np.cumsum(index_weighted2)
cum_index_share2 = np.insert(cum_index2 / cum_index2[-1], 0, 0)
```

```
gini2 = weighted_gini(index2, pop2)

# === Plot Lorenz curve ===

plt.figure(figsize=(6.5, 6.5))

plt.plot(cum_pop_share2, cum_index_share2, label='Lorenz Curve (Population-weighted)', linewidth=2)

plt.plot([0, 1], [0, 1], '--', color='gray', label='Line of Equality')

plt.xlabel('Cumulative Share of Population')

plt.ylabel('Cumulative Share of Transportation Index (e.g., TDI)')

plt.title(f'Lorenz Curve for Shifted Index (Gini = {gini2:.3f})')

plt.legend()

plt.grid(True)

plt.tight_layout()

plt.show()plt.figure(figsize=(7, 7))

plt.plot(cum_pop_share, cum_index_share, label=f'2020 (Gini = {gini:.3f})', linewidth=2)

plt.plot(cum_pop_share2, cum_index_share2, label=f'2025 (Gini = {gini2:.3f})', linewidth=2)

plt.plot([0, 1], [0, 1], '--', color='gray', label='Line of Equality')


plt.title('Lorenz Curves for 5D Index in 2020 and 2025')

plt.xlabel('Cumulative Share of Population')

plt.ylabel('Cumulative Share of 5D Index')

plt.legend()

plt.grid(True)

plt.tight_layout()

plt.show()
```

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