Highlights:

- There is a significant spatial and racial mismatch between delivery supply and demand.
- Compact or proximity logistics is indirectly associated with more equitable delivery areas.
- Racial segregation, supply centrality, and social capital are significant, interacting factors.

Abstract: Populations of color (POC) are disproportionately exposed to delivery-related traffic despite ordering fewer packages than White populations. This study uses structural equation modeling (SEM) to examine which urban form and socio-economic factors contribute to these racial disparities in 39 U.S. metropolitan statistical areas (MSAs). Of particular interest is "logistics sprawl," which has lengthened distances between freight supply and demand. Prior research links sprawling urban form to the uneven distribution of externalities, social deprivation, and accessibility. This connection remains underexplored in urban freight research. Findings reveal segregation, social capital, and supply centrality mediate and condition the equity benefits of more logistically compact urban form, or "proximity logistics." Though promising, urban freight management strategies alone cannot address environmental inequities without confronting the underlying socio-economic and political structures that reproduce them.

Keywords: Urban Freight, Last-mile Delivery, E-commerce, Environmental Justice, Equity

Word count: 6,674 (excluding references and title page)

1.Introduction

Populations of color (POC) are disproportionately exposed to delivery-related traffic despite ordering fewer packages than White populations (Fried et al., 2024b, 2024c). It is not the neighborhoods with the most frequent online shoppers that receive the lion-share of delivery traffic, but those in proximity to warehousing and distribution centers (W&D) and highways that respectively generate and channel resulting delivery trips. In other words, racial disparities in exposure to delivery traffic is intrinsically linked to the spatial organization of people, logistical facilities, and infrastructure—i.e, urban form.

Addressing racial disparities in traffic exposure most readily speaks to environmental justice (EJ) scholarship (Antonczak et al., 2023). EJ scholars measure Black and Hispanic Americans' disproportionate exposure to transport-related air pollution (Demetillo et al., 2021; Kerr et al., 2024; Lathwal et al., 2022; Marshall et al., 2014; Ramirez-Ibarra and Saphores, 2023), hazardous materials spills (Schweitzer, 2006), injuries and fatalities from vehicle crashes (Yuan and Wang, 2021), and noise (Yildirim and Arefi, 2021). The consequence is an accumulation of adverse health costs and years of life lost. However, racial disparities are not isolated in time. They are echoes of historically illiberal urban development practices that locked-in many of today's land use patterns. For instance, research partly connects "redlining," a prominent example of the racialized mortgage lending practices endemic throughout the early-to-mid 20th Century, to Black Americans' disproportionate exposure to air pollution today (Lane et al., 2022).

The persistence of racial disparities is also not isolated to environmental quality. Few systems in the urban and market environment, including transport logistics, are designed with fairness as its leading principle. Schweitzer and Stephenson (2007) note researchers' tendency to decouple EJ from social and economic theories of urban inequality—be that residential sorting (Banzhaf et al., 2019), political economy (Smiley, 2020), or agglomeration economics (Bowen et al., 2009)—which they akin to "decanting old wine into new bottles" (p. 328). In any case, a robust accounting of environmental disparities requires an accounting of the urban spatial structures that underpin them.

Studies that identify environmental disparities without contextualizing these underpinnings risk offering or implying reductive solutions to complex problems. For example, banishing W&D to the sparsely populated hinterlands might seem a natural solution to minimizing freight traffic disparities in the city. However, relocating W&D from the urban center to the suburban outskirts has also generated unintended socio-economic and environmental consequences (Aljohani and Thompson, 2016; Holguín-Veras et al., 2021).

Furthermore, this study inspects relevant spatial and socio-economic factors that shape racial disparities in last-mile delivery externalities. Of particular interest is "logistics sprawl," or the suburbanization of freight-intensive activity. Researchers link sprawling urban form to the uneven distribution of external costs, social deprivation, and accessible opportunities (Wei and Ewing, 2018). This linkage has not been made in urban freight research (Fried et al., 2024a), despite the relevance of logistical urban form in generating unequal exposure to freight trips. This study tests if logistically compact delivery areas are more racially equitable. It also contributes insights from the urban and regional sciences by exploring the effects of residential segregation and social capital.

The following literature review highlights key features in our understanding of urban form, logistics, and racial inequity (*Section 2*). The review identifies covariates in a generalized structural equation model (SEM) that cross-sectionally examines racial disparities between online ordering and last-mile delivery traffic exposure in 39 U.S. metropolitan statistical areas (MSAs) (*Section 3*). The results show segregation, social capital, and supply centrality mediate and condition the disparity-producing effect of logistically sprawled delivery service areas (*Section 4*). Findings contribute to discussions around "proximity logistics," with implications for urban planners that seek to center equity in transport and land use decisions (*Section 5*).

2. Literature review

Freight is a product of spatio-economic and -political structures that sort populations and businesses within and between regions (Anas et al., 1998; Giuliano et al., 2018; Hesse, 2020). As people, firms, and infrastructure are not uniformly sorted in space, freight activity will inevitably concentrate in some areas more than others. Coasian economic perspectives suggest freight-intensive firms bargain with communities' willingness to accept compensation (usually jobs) in exchange for disamenities like pollution (Banzhaf et al., 2019). Efficient outcomes assume no transaction costs, perfect information, and sovereignty over environmental decisions.

In practice, however, symmetry in information and power is far from the norm. Firms could systematically locate W&D in communities with the lowest bargaining power due to an array of social, political, and economic conditions (Ataullah et al., 2023; Bullard, 2000; Cole and Foster, 2001; Maantay, 2002; Mohai and Saha, 2015; Schelly and Stretesky, 2009). But regardless of *why* environmental disparities occur, it is beyond debate that they do. This section does not revisit decades of scholarship that concerns U.S. urban development and its racially disparate impact. Rather, it will build a baseline understanding of urban freight, racial inequity, and three covariates: segregation, sprawl, and social capital.

2.1 Segregation

Longitudinal analyses link unequal pollution exposure to racial and income-based housing segregation (Shertzer et al., 2022), with EJ research largely debating the extent to which land and housing markets serve as the sorting mechanism. These competing hypotheses, "disparate siting" versus "post-siting demographic change," concern whether polluting land uses move toward residents or *vice-versa* (Mohai and Saha, 2015 cf. Been, 1994). Maantay's (2002) analysis in New York City finds notable evidence for the former, revealing a history of "expulsive" industrial zoning that contributed to the encroachment of manufacturing facilities into predominantly Black neighborhoods. Whittemore (2017) applies Maantay's mixed-method approach to Durham (North Carolina), reconfirming a pattern of disparate heavy industry siting in Black communities. However, the Durham study concludes with hope: much of the heavy industrial zones that historically burdened marginalized communities have been "downzoned" into lighter industrial land uses.

However, as manufacturing offshored and the U.S. transitioned largely from a production economy to a consumption economy, W&D gradually superseded the factory (Cidell, 2011; Hesse, 2020). W&D typically classify as light industrial land uses and are permitted with less environmental oversight than their more visibly noxious progenitors (Fried et al., 2025). A growing body of work has investigated patterns of disparate W&D siting (Tejada and Conway, 2024; Yuan, 2018), and its environmental impact on adjacent communities due to high volume of freight traffic these facilities generate (Jaller et

al., 2022; Kerr et al., 2024). While DeSousza et al.'s (2022) spatially lagged model find mixed effects of W&D density on various health costs, it still shows substantial disparities for low-income and Hispanic populations in Southern California. As such, disparate W&D siting presents an underexplored context for environmental inequities faced by racially marginalized populations today.

To account for the sorting processes that may underlie disparate siting, the model includes the racial dissimilarity of each delivery service area as an indicator of segregation. Segregation has long been linked to the concentration of intergenerational poverty within cities (Massey and Denton, 1993), and within the context of urban sprawl (Wei et al., 2023; Wei and Ewing, 2018). While the spatial severity of racial segregation has somewhat lessened since the apartheid-levels of the early-to-mid 20th Century, its structural effects persist across geographies and institutions (e.g., Prasanth et al., 2024).

2.2 Sprawl

The outward expansion of people and firms is a focal point of urbanist debate. Research generally finds sprawled metropolitan areas are more emission intensive, in part, due to the greater spatial distances between residences and opportunities that lead to higher rates of private vehicle travel (Jones and Kammen, 2014). Most studies that examine the movement of W&D away from urban centers reach similar conclusions regarding freight transport's increasing vehicle miles traveled (VMT) and emissions (e.g., Dablanc and Rakotonarivo, 2010).

However, sprawl's multi-dimensionality helps it elude first-order definitions and causations (Brueckner et al., 2001; OECD, 2018). In that sense, "logistics sprawl" presents a narrow expression of broader spatio-economic and political processes that concern locational decisions made by people and firms. Research has enriched our economic understanding of logistics sprawl and its impacts by comparing various methodologies based on more robust agglomeration indicators (Kang, 2020a, 2020b; Rivera et al., 2014; Rivera-Gonzalez et al., 2023), or using GPS traces from trucks to validate measures (Trent and Joubert, 2022).

These approaches paint a nuanced picture of logistics sprawl's relationship to environmental impact. For instance, Sakai et al. (2017) find demand decentralization offsets VMT generated by sprawling W&D in Tokyo. Logistics sprawl may well be an efficient response to the sprawl of people and businesses. Gardrat (2021) suggests increasing freight-related VMT is a result of two distending forces in Lyon, France: the sprawl of freight emitting activities and the densification of freight consuming activities. Other cities do not exhibit logistics sprawl at all (Dablanc et al., 2014), and show signs of logistics centralization or "anti-sprawl" (Krzysztofik et al., 2019). Nevertheless, it may be difficult to extricate the forces that create *logistics* sprawl from those that create *urban* sprawl.

In the latter case, "Smart Growth" and "New Urbanist" advocates and researchers have increasingly analyzed the equity benefits of compact urban development. For instance, researchers have linked urban sprawl to greater inequities in income (Lee et al., 2018), air pollutant-related cancer risks (Tsoulou, 2018), social capital (Nguyen, 2010), and socio-economic mobility (Ewing et al., 2016). It is reasonable to expect that environmental disparities are less pronounced in more compact urban environments, though this relationship may be indirect.

2.3 Social capital

Putnam (2001, p. 9) famously defines social capital as "connections among individuals—social networks and the norms of reciprocity and trustworthiness that arise from them." Scholars typically conceptualize social capital as a form of resource conversion (Bourdieu, 1986), much like factories produce physical capital or education creates human capital, and as a rubric for community governance and collective action (Bowles and Gintis, 2002; Ostrom and Ahn, 2009). Mainly, social capital refers to a community's ability to leverage social ties—both within and between groups—to achieve mutually beneficial outcomes.

One major EJ theory suggests pollution follows a "path of least resistance" (Bullard, 2000; Cole and Foster, 2001; Schelly and Stretesky, 2009). Firms may locate W&D based on the ability of high-capital neighborhoods (presumed to be high-income, well-educated, predominantly White and home-

owners) to deflect them from their backyards, and/or the inability of low-capital neighborhoods (conversely presumed to be low-income, less-educated, and predominantly Black or Hispanic) to resist them in theirs (Pastor, 2004).

To this end, evidence of the linkage between social capital and pollution disparities has been mixed. Ataullah et al.'s (2023) longitudinal, county-level analysis of carcinogenic waste finds high social capital can reduce certain toxic releases and facility siting, but its influence diminishes when the polluting industry plays a large role in the local economy. Ard & Fairbrother (2017) and Smiley (2020) find that not all forms of social capital are associated with pollution disparities, nor are racial minority or low-income communities always poor in social capital. Moreover, pollution may have a reverse effect on social capital—high exposure can itself corrode collective efficacy (Brown, 2022).

Operationalizing social capital's multi-dimensional complexity remains a central challenge. Researchers may produce divergent findings on social capital due to the varied definitions, proxies, and latent constructs they employ to measure it (Gannon and Roberts, 2020). For instance, Fraser et al. (2022) draw from the American Community Survey to derive bonding, bridging, and linking indices that explain up to 49% of variation in COVID-19 outcomes, whereas Chetty et al. (2022) use Facebook data to link economic connectedness with upward socio-economic mobility. Nevertheless, the prominence of social capital in sociological theories of urban inequality—and its limited exploration in studies of traffic exposure disparities (Schwanen et al., 2015, p. 131)—warrants closer examination.

2.4 E-commerce as a case study

E-commerce has transformed the "consumption geography" of cities, with major implications for urban freight transport and land use (Beckers et al., 2022; Buldeo Rai, 2021). It positions households as key supply chain agents, especially urban, high-income, educated, and White populations who order more frequently (Figliozzi and Unnikrishnan, 2021; Fried et al., 2024c, 2024b; Hood et al., 2020). This shift stems some commercial vehicle traffic away from truck corridors into residential

neighborhoods and draws some logistics facilities closer to urban centers to facilitate faster, more reliable deliveries (Fried and Goodchild, 2023).

E-commerce's net-environmental costs remain an open question. Despite constituting a lower share of overall traffic volume—less than 10% in most countries—urban freight contributes nearly half of health-adverse NOx air pollution (Minet et al., 2020) and is an accelerating source of road crashes (McDonald et al., 2019). However, e-commerce emissions depend greatly on consumer/operator behaviors and urban form (Buldeo Rai et al., 2022b; Jaller et al., 2023; Jaller and Pahwa, 2020; Wygonik and Goodchild, 2018). For instance, how far the operator must drive to reach the consumer, how efficiently they are utilizing vehicle capacity, whether the consumer chooses next-day or deferred shipping, or if consumers choose to receive the package at their doorstep or a nearby parcel locker. Urban form factors, such as block density and road circuity, also affect delivery times and route selection (Amaral and Cunha, 2020).

E-commerce presents new considerations for compact urban development. "Proximity logistics" and "freight efficient land uses" offer frameworks for minimizing private and external costs by reducing spatio-temporal distances between freight supply and demand (Buldeo Rai, 2023; Buldeo Rai et al., 2022a; Holguín-Veras et al., 2021). Cases in Paris (France) and Rotterdam (The Netherlands), for instance, demonstrate how W&D can integrate into neighborhoods, fulfill delivery needs of nearby businesses and residents, enable delivery by lower-impact vehicles (e.g., electric cargo bikes, Gunes et al., 2024) and host mixed-use opportunities such as restaurant suppliers and rooftop farms (Kin et al., 2024). Furthermore, this analysis examines whether logistics sprawl—or its counterpoint, proximity logistics—can help explain racially disparate e-commerce externalities.

3. Methodology

This study estimates online ordering behavior and consequent residential freight trip generation using an activity-based model that draws on the 2017 National Household Travel Survey and Amazon facility locations. Fried et al. (2024b) detail the methodology and limitations of the approach. The

study models and analyzes the distribution of cargo van VMT across race and income groups in 41 MSAs in 2017. The study finds race a stronger determinant of delivery disparities than income alone. Consequently, this study tests the effects of proximity logistics on racial disparities while controlling for income.

This paper adds to Fried et al.'s (2024b) methodology in two ways. I calculate the "middle-mile" VMT by trucks between sortation centers (SC) and last-mile delivery stations (LMDS). I also introduce fixed external cost coefficients. The following sections describe the added steps and building the SEM.

3.1 Adding middle-mile truck flows and calculating costs per package-mile

LMDS serve as final touchpoints for most forms of urban home delivery (Fried and Goodchild, 2023). We assume diesel cargo vans exclusively serve the last-mile. Although Amazon has accelerated their procurement of electric vans (Amazon, 2023), the study's data constrains the analysis to years prior to these investments. Moreover, a substantial degree of observed inequity between racial groups occurs due to the middle-mile movement of trucks between LMDS and SC (Fried et al., 2024c).

Therefore, this study estimates the two-way VMT of truck flows between the two facilities. Most MSAs have one SC; however, six do not at the time of the observed data. In these cases, the analysis assumes truck trips originate from a point near the MSA's largest airport (Rodrigue, 2020). Similar to Fried et al. (2024b), the network analysis implements the open-sourced R5R package and makes static assumptions regarding vehicle utilization (2,000 packages per trip, see Fried et al., 2024c).

Carriers also transport packages on a diverse range of infrastructures, from quiet residential streets to congested inter-state highways, which generate distinct costs (*see Table 1*). Most U.S.-based cost estimates do not differentiate between vehicle classes nor urban road typologies (Demir et al., 2015), presenting difficulties when attempting to model the external costs of e-commerce. Cárdenas et al. (2017) develop external cost indices for home delivery in Belgium, which this study adapts. This

study defines a block group as an "urban road type" if its population density is more than one standard deviation above the MSA mean (~3,000 people/sq. mi), and a delivery trip terminates or passes through it. The analysis also determines middle-mile truck flows occur mostly on inter-state and regional highways (Essen et al., 2020).

EU diesel emissions standards and road conditions are not equivalent to those in the United States. However, it is beyond the scope of this study to validate the *aggregate* results of external cost calculations. Rather, the subsequent model seeks to explain the *distribution* of these costs between POC and White populations.

	Road type	Air pollution	Crashes	GHG emissions	Noise	Congestion (delay)	Total avg. cost
Cargo van	*Urban*	*1.72**	*2.67*	*1.54**	*0.04****	*23.81*	*29.80*
	Suburban	*1.65**	*2.67*	*1.30**	*<0.00*****	*16.80*****	*22.42*
Truck	*Highway*	*0.45***	*0.58*	*0.53***	*3.73****	*1.91*	*7.20*

Table 1: Static external cost coefficients ($-cents/package-mile) and assumptions (adapted from Cárdenas et al., 2017; Essen et al., 2020). NOTE: *Euro V, diesel light goods vehicle; ** Euro V, 17T heavy goods vehicle; ***day-time congestion conditions; ****less congested road conditions.

3.2 What is fair? Selecting an outcome variable

Distributive justice in the liberal, Western philosophical and economic tradition encompasses an array of normative and positive frameworks. However, many common indicators used to evaluate equity provide limited insight into the actual distribution of costs/benefits. The area under a Lorenz curve (i.e, Gini coefficient), for instance, is arguably the most common measure of absolute inequality.

However, it is largely uninformative when it comes to ranking outcomes between each other, comparing population groups, or determining the direction of inequality (Karner et al., 2025).

Tessum et al. (2019) proposes a more intuitive indicator, suggesting an inequity occurs when a population group's pollution exposure exceeds the pollution they generate from their consumption. In e-commerce, this could mean that an inequitable outcome occurs when a population group receives external costs disproportionate to the external costs generated (or marginal benefit received) by this group's ordering share. Since consumption-based benefits are likely proportional to consumption volume, this paper adopts a novel "fair share" ratio (*FS*) shown in *Equation 1*.

Equation 1:

$$FS_i = \frac{\sum_i Cost_{POC} \Big/ \sum_i Cost_{total}}{\sum_i Delivey_{POC} \Big/ \sum_i Delivery_{total}}$$

Where:

- *i* is the service area that aggregates Census block groups.
- The numerator is the share of costs borne by POC in service area *i*.
- The denominator is the share of deliveries received by POC in service area *i*.

FS=1.0 suggests POC receive external costs in proportion to the packages they receive. Whereas values greater than 1.0 suggests POC bear higher external costs despite consuming less than White populations. In addition to being intuitive, the ratio also controls for the effect of delivery behavior in the model.

3.3 Selecting covariates and identifying relational paths

I use SEM to estimate both the direct and indirect effects of logistics sprawl/proximity logistics on racial disparities in last-mile delivery. SEM enables the evaluation of theoretically grounded models against observed data (Ewing et al., 2016). *Table 2* summarizes the endogenous and exogenous

variables of interest. Endogenous variables represent first-order outcomes in the model and mediate the influence of exogenous variables (Hayes, 2022). The study draws on the theoretical foundations outlined in the literature review to identify variables and specify relational paths (see *Figure 1*).

Since the underlying demand model assumes LMDS deterministically serve populations closest to the facility, the unit of analysis are the Thielssen-defined service areas (see *Figure 1*). The model also combines adjacent spillover facilities into singular points (Fried et al., 2024b). Consequently, the authors observe that LMDS are generally dispersed throughout their respective MSAs, often with large distances between facilities. If person *x* is served by closest LMDS *a*, it is less likely they would be exposed to the external costs generated by LMDS *b* serving person *y*, or to a lesser degree. Although a simplification, validating the impact of LMDS proximity and distance decay depend on an array of confounding factors not tested in this study, e.g., the atmospheric conditions that transport and chemically transform air pollutants. I treat service areas—and the populations they contain—as independent from one another (Wygonik & Goodchild, 2018).

This study hypothesizes that logistically sprawled service areas are more inequitable than logistically compact delivery areas. There are two primary variables of interest:

- Supply centrality (*s_cent*) measures the Euclidean distance between LMDS and the weighted employment centroids of goods producing industries. The analysis defines "goods producing" industries by their two-digit North American Industry Classification System (NAICS) code: Manufacturing (*NAICS 31-33*), Wholesale Trade (*NAICS 42*), Retail Trade *(NAICS 44-45*), and Transportation & Warehousing (*NAICS 48-49*) (Kang et al., 2020b). Drawing on Bowen's (2009) theory of EJ and agglomeration, the model assumes *s_cent* has endogenous effects.
- Demand centrality (*d_cent*) measures the network distance between LMDS and delivery demand centroids. This variable is the volume-weighted mean route-distance traveled by cargo vans to reach home consumers. This variable is an e-commerce equivalent to Rivera-Gonzalez et al.'s (2023) supply chain-focused metric of spread.

Endogenous and control variables include:

- Residential segregation of POC (*DI*) is the frequently used Dissimilarity Index, with demographic data provided by the U.S. Census Bureau 5-year American Community Survey (ACS). The DI equation follows, where a high DI indicates higher racial dissimilarity or segregation across block groups *j* contained within service area *i*:

Equation 2:

$$DI_i = \frac{1}{2}\sum_{j \in i}\left| {}^{POC_j}\!/_{POC_i} - {}^{White_j}\!/_{White_i} \right|$$

- Social capital (*socap*) is a recent iteration of a composite index developed by Fraser et al. (2022) for 2017. The index is composed of three subindices: bonding (i.e., lower fractionalization in racial and ethnic make-up, gender, education, employment, and income), bridging (i.e., higher concentrations of religious, charitable, labor, and civic organizations), and linking (i.e., higher concentrations of voters, government employees, and political activities). *Socap* is the population-weighted mean index of Census tracts contained within a service area.
- Compactness *(compact)* is another composite index, developed by Ewing and Hamdi (2014) at the MSA-level. The index comprises of four subindices: density (i.e., employment and population densities), mixed-use (i.e., job-population balance and walkability), centering (i.e., spatial variation in density), and street factors (i.e., intersection and block density). The index centers the mean at 100, where greater values indicate a more compact environment.
- *Size* controls for the area of the delivery service area.
- The volume-weighted network distance traveled by trucks (*t_dist*) controls for the distance between SC and LMDS.
- Location Quotient *(LQ)* compares the relative employment share of goods producing industries in the MSA compared to other sectors and across the United States. LQ is defined

in *Equation 3,* where a value greater than 1.0 signifies a stronger clustering of goods producing industries in the MSA.

Equation 3:

$$LQ_{MSA} = \frac{Employment_{Goods}^{MSA} \Big/ Employment_{total}^{MSA}}{Employment_{Goods}^{USA} \Big/ Employment_{total}^{USA}}$$

	Variables	Name	Theory	Relevant source
Outcome	Fair share ratio	*FS*	-	Author's elaboration
Endogenous	Residential segregation	*DI*	*Segregation*	(Ewing et al., 2016; Massey and Denton, 1993; US Census Bureau, 2017a)
	Supply centrality	*s_cent*	*Sprawl*	(Rivera-Gonzalez et al., 2023; US Census Bureau, 2017b)
	Social capital	*socap*	*Social capital*	(Fraser et al., 2022)
Exogenous	Location quotient (MSA-level)	*LQ*	*Sprawl*	(Kang, 2020b; Rivera et al., 2014; US Census Bureau, 2017b)
	Median household income	*income*	*Segregation*	(Ewing et al., 2016; Massey and Denton, 1993; US Census Bureau, 2017a)
	Compactness (MSA-level)	*compact*	*Sprawl*	(Ewing and Hamidi,

				2014)
	Demand centrality	*d_cent*	*Sprawl*	(Fried and Goodchild, 2023; Wygonik and Goodchild, 2018)
	SC distance to LMDS	*t_dist*	*Sprawl*	(Fried et al., 2024c)
	Service area size (sq. mi.)	*size*	*Sprawl*	(Fried and Goodchild, 2023; Wygonik and Goodchild, 2018)

Table 2: SEM variables and data sources.

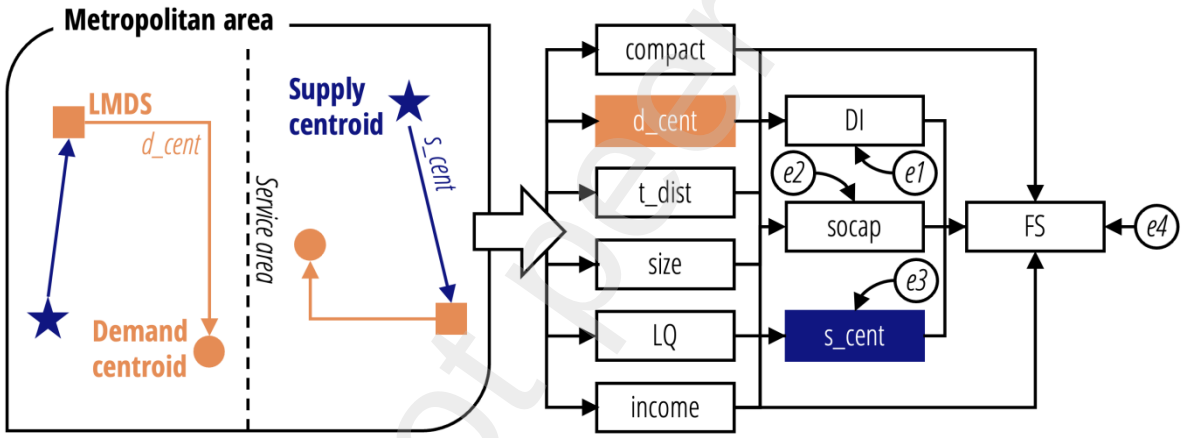

Figure 1: Visualizing variables of interest for two delivery service areas (left) and path diagram (right).

Structural equations are an integrated system linear regression models, defined by *Equations 4-8* below.

Equations 4-8:

$$FS_i = \beta_1 DI_i + \beta_2 socap_i + \beta_3 s\_cent_i + \beta_4 d\_cent_i + \sum \beta_{5-9}\, controls$$

$$DI_i = \beta_{10} d\_cent_i + \sum \beta_{11-15}\, controls$$

$$socap_i = \beta_{16} d\_cent_i + \sum \beta_{17-21}\, controls$$

$$s\_cent_i = \beta_{22} d\_cent_i + \sum \beta_{23-27}\, controls$$

Equation 4 represents the direct effects of all variables on FS, while *Equations 5-8* show the indirect effects of the exogenous variables. Not represented by the base equations, the model finds significant interaction between the endogenous variables. The next section discusses these moderated and conditional effects further.

4. Results

I hypothesize that large distances between delivery supply and demand partially explain racial disparities in last-mile delivery. This section examines this spatial and racial mismatch across two geographic-levels, MSAs and service areas, drawing on descriptive statistics and SEM respectively.

4.1 Spatial and racial mismatch between delivery supply and demand across MSAs

Figure 2 plots the POC external cost exposure and ordering behavior in 41 MSAs analyzed by Fried et al. (2024b). The mean FS across MSAs is 1.55. That is, POC are exposed to 55% more external costs relative to their delivery share. Among the most unfair MSAs are those in the industrial Midwest: St. Louis, MO (STL, FS=3.72), Cleveland, OH (CLE, FS=3.59), Cincinnati, OH (CVG, FS=3.40), Indianapolis (IND, FS=2.89), and Milwaukee (MKE, FS=2.65).

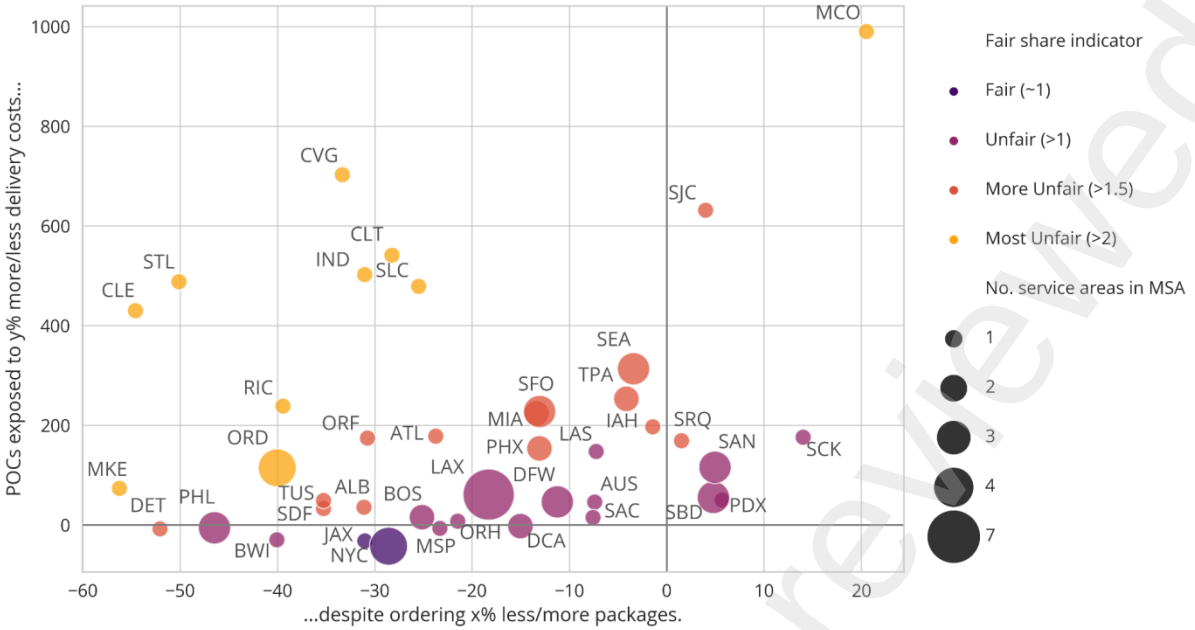

Figure 2: Plotting POC fair share indicators across MSAs. NOTE: Labels represent the IATA code of the MSA's largest city for better visualization.

All five MSAs exhibit above-average LQ, exceeding both the sample mean (LQ=0.93, see *Table 3*) and the 1.0 threshold—indicating that goods producing employment is more concentrated in these areas compared to the broader national economy. MKE has the highest LQ in the sample at 1.21. These MSAs' compactness indices are also lower than the sample mean (*compact*=97.41, see *Table 3*) and the mean-center at 100, except for MKE (*compact*=130.35). Additionally, three MSAs (MKE, CLE, and STL) are the most racially segregated regions in the sample (*DI* between 62.47 and 63.08). *Figure 3* illustrates that high LQ, DI, and sprawl are significantly correlated with a higher FS indicator. Regions with strong specialization in freight-intensive sectors, sprawling urban form, and entrenched racial segregation may accentuate last-mile delivery disparities.

	Mean	**Median**	**Variance**
FS	1.55	1.49	0.43
DI	43.16	42.25	94.90
socap	49.60	49.61	33.23

s_cent (mi)	8.14	8.25	16.02
income ($ thou.)	72.87	69.81	2.46e5
d_cent (mi)	19.63	19.16	44.23
t_dist (mi)	23.04	21.85	214.63
size (thou. sq. mi)	3.07	2.13	942.14
compact (MSA-level)	97.41	98.88	543.78
LQ (MSA-level)	0.93	0.93	0.02

Table 3: Summary statistics of outcome, predictor and control variables.

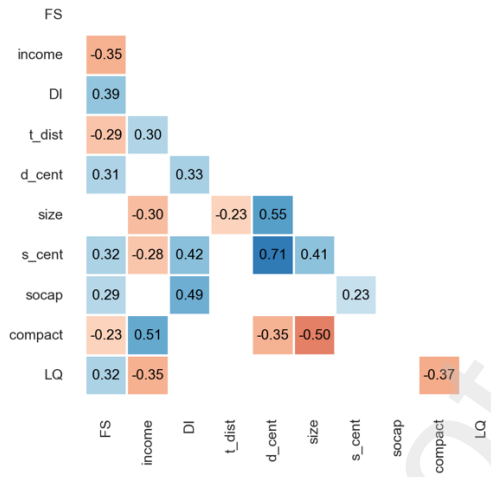

Figure 3: Pearson's correlation matrix showing significant correlations only (p <0.1)

Only two MSAs in the sample exhibit a "fair" distribution of delivery externalities: Jacksonville, FL (JAX, FS=0.99) and New York City (NYC, FS=0.87). However, their relationship to MSA-level attributes is less clear. Both have LQ below 1.0, though JAX is above the sample mean (*LQ*=0.96). Urban form also differs: JAX is highly sprawled (*compact*=80.85), while NYC is among the most compact MSAs in the sample (*compact*=131.70). Additionally, NYC's delivery environment is

moderately more compact. NYC's mean last-mile delivery distance (*d_cent*) between supply and demand is 20.5 mi compared to 26.1 and 28.0 in CLE and STL, respectively.[1]

Figure 4 maps the POC share, LMDS locations, and delivery demand centroids in CLE, STL, and NYC. CLE and STL show a clear spatial and racial mismatch between where delivery demand is centered and LMDS are sited. Across Census block groups, the share of POC within a half mile of LMDS is 76.8% versus 27.3% within a half mile of the demand centroid in CLE (64.5% lower near the centroid), and 70.5% versus 12.8% in STL (81.8% lower).

In fact, this spatial and racial mismatch holds across the entire MSA sample. *Table 3* reports the population-weighted share of POC in block groups within a half mile of an LMDS versus those within a half mile of the delivery demand centroid. On average, neighborhoods near LMDS have about a third higher POC share. These patterns provide important context for the SEM analysis, which will partially explain how proximity logistics and segregation affect these racial disparities.

[1] The 2017 Manhattan (NYC) location was the business address of a last-mile delivery pilot that is no longer operational as of 2025 (confirmed via personal communication with the company). There is currently no LMDS operating in Manhattan.

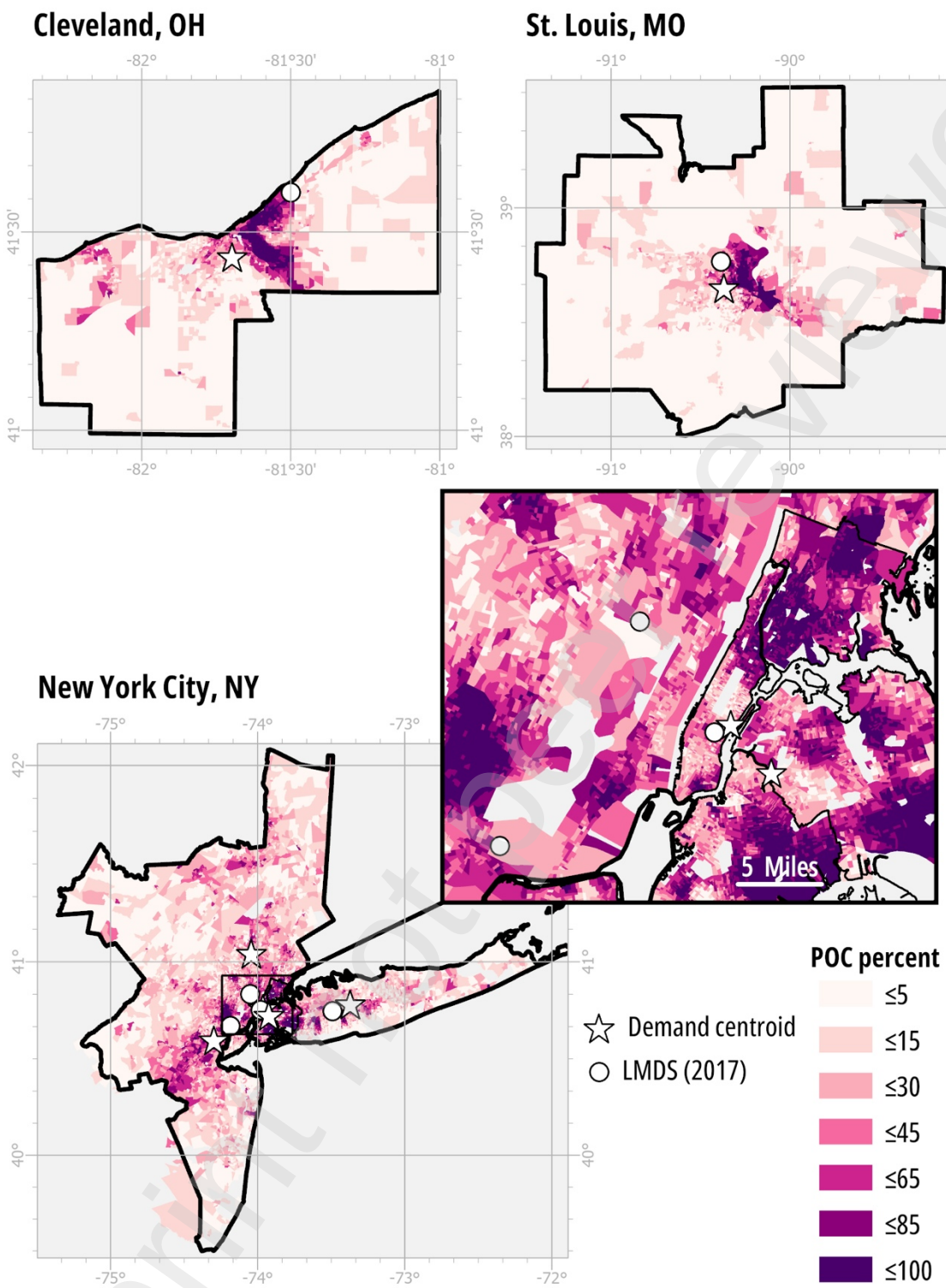

Figure 4: Maps of POC percent share, LMDS locations and delivery centroids in fair (NYC) and unfair MSAs (CLE and STL) in 2017.

		Population-weighted POC percent share			
	Block groups w/in 0.5 miles	mean	median	variance	Welch's t-test (H0: LMDS=Demand)
LMDS	247	47.72	45.84	603.82	<0.001***
Demand	252	35.99	30.56	639.78	

Table 3: Summary statistics of population-weighted POC percent share for block groups within 0.5 miles of an LMDS and demand centroid.

4.2 SEM findings

Table 3 presents the final model. All variables are mean-centered to allow direct comparison of coefficients. I also estimate standard errors and significance levels using percentile bootstrapped confidence intervals to enhance robustness and correct bias (Tibbe and Montoya, 2022). As discussed, the unit of analysis is the LMDS-based service area, of which there are 69 across the 41 MSAs. Due to gaps in Massachusetts employment data that produces null values for the *compact* variable, two MSAs—Boston (*BOS*) (n_{LMDS}=4) and Worcester (*ORH*) (n_{LMDS}=1)—are excluded from the analysis. As such, the final model includes 65 service areas.

Because a model specified with all direct and indirect paths and covariances is just-identified (df=0), conventional fit indices (e.g., χ^2, CFI, RMSEA) are not informative (Hayes, 2022). To evaluate the contribution of interaction terms, I compare a baseline model without interactions (see *Figure 1*) to a more complex model that includes them (see *Table 4*). The lower Bayesian Information Criterion

(BIC) value for the interaction model indicates that the additional parameters improve relative fit, supporting their inclusion. I highlight major finding below.

Variable paths	Coef.	Std. e	Variable paths	Coef.	Std. e
FS←DI	2.38	2.61	DI:s_cent←d_cent	0.78***	0.11
FS←socap	1.44	1.12	DI:s_cent←t_dist	0.05	0.09
FS←s_cent	11.49**	6.49	DI:s_cent←compact	0.27***	0.11
FS←DI:s_cent	-13.67**	7.70	DI:s_cent←LQ	0.13	0.09
FS←DI:socap	-3.47	3.33	DI:s_cent←income	-0.28***	0.10
FS←socap:s_cent	-14.00**	7.10	DI:s_cent←size	-0.14	0.11
FS←DI:socap:s_cent	16.78**	8.37	DI:socap←d_cent	0.61***	0.14
FS←d_cent	0.09	0.19	DI:socap←t_dist	0.07	0.12
FS←t_dist	-0.23**	0.12	DI:socap←compact	0.29***	0.15
FS←compact	-0.01	0.17	DI:socap←LQ	0.11	0.12
FS←LQ	0.10	0.12	DI:socap←income	-0.24**	0.13
FS←income	-0.12	0.14	DI:socap←size	-0.32**	0.14
FS←size	0.07	0.17	socap:s_cent←d_cent	0.70***	0.11
DI←d_cent	0.62***	0.12	socap:s_cent←t_dist	-0.01	0.09
DI←t_dist	0.12	0.15	socap:s_cent←compact	0.18*	0.11
DI←compact	0.38***	0.12	socap:s_cent←LQ	0.03	0.09
DI←LQ	0.17	0.13	socap:s_cent←income	-0.19*	0.10
DI←income	-0.32***	0.14	socap:s_cent←size	-0.03	0.11
DI←size	-0.29**	0.14	DI:socap:s_cent←d_cent	0.77***	0.11
socap←d_cent	0.37***	0.15	DI:socap:s_cent←t_dist	0.03	0.09
socap←t_dist	-0.08	0.12	DI:socap:s_cent←compact	0.23**	0.12

socap←compact	0.05	0.15	DI:socap:s_cent←LQ	0.11	0.09
socap←LQ	-0.07	0.12	DI:socap:s_cent←income	-0.25**	0.10
socap←income	0.03	0.14	DI:socap:s_cent←size	-0.19*	0.11
socap←size	-0.25**	0.15	**R^2**		
s_cent←d_cent	0.69***	0.10	socap	0.13	
s_cent←t_dist	0.01	0.09	DI	0.34	
s_cent←compact	0.22**	0.11	s_cent	0.56	
s_cent←LQ	0.05	0.09	FS	0.47	
s_cent←income	-0.21***	0.10	DI:socap	0.30	
s_cent←size	0.05	0.10	DI:s_cent	0.56	
			socap:s_cent	0.56	
			DI:socap:s_cent	0.51	
			BIC_0	710.94	
			$BIC_{interaction}$	103.83	

Table 4: Standardized direct and indirect effects in the delivery service area interaction model (n=65). NOTE: * p <0.1, ** p<0.05, *** p<0.01

4.2.1 Racial segregation, supply centrality, and social capital significantly interact

Table 4 reports the effects of the endogenous and exogenous variables. *DI* and *s_cent* exhibit the hypothesized positive associations with FS: service areas are more unfair when segregation is higher and goods-producing jobs are more spatially dispersed. *Socap* has a weaker, positive relationship. Service areas are more unfair when social capital is high. These variables significantly interact, meaning their effects on *FS* are conditional on one another.

	Direct	**Indirect**	**Total**
DI	2.38	0.00	2.38

socap	1.44	0.00	1.44
s_cent	11.49**	0.00	11.49**
DI:socap	-3.47	0.00	-3.47
DI:s_cent	-13.67*	0.00	13.67*
socap:s_cent	-14.00**	0.00	-14.00**
DI:socap:s_cent	16.78**	0.00	16.78**
income	-0.12	-0.11***	-0.23**
d_cent	0.09	0.21***	0.30***
t_dist	-0.23**	0.05	-0.18
size	0.07	-0.13*	-0.05
compact	-0.01	0.09**	0.08
LQ	0.10	0.13	0.23**

Table 5: Standardized total effects on delivery fair-share (FS). NOTE: * p <0.1, ** p<0.05, *** p<0.01

Figure 4 probes this three-way interaction by examining the relationship between *FS* and *DI* at high (↑) and low (↓) levels of *s_cent* and *socap* (defined as the mean ±1 standard deviation). The most notable effect occurs when *s_cent* and *socap* are high. These conditions substantially accentuate the correlative strength between racial segregation and delivery unfairness.

At first glance, the conditional effect of high social capital appears to contradict the "path of least resistance" theory. Prior research suggests that high social capital may mitigate concentrated environmental burdens (Ataullah et al., 2023). However as Ataullah et al. (2023) and others note (Gannon and Roberts, 2020; Schwanen et al., 2015), the effects of social capital are heterogeneous, context-dependent and, at times, can produce negative externalities.

For instance, Ataullah et al. (2023) note that social capital's protective effects diminish when the employment share of the polluting industry is high. Communities may be less willing (or less able) to oppose a siting when that industry constitutes an important source of livelihood. This study's results appear aligned with this observation. The total effects of *LQ* and *income* are positively and negatively associated with FS, respectively. This relationship may reflect weaker resistance to LMDS siting, and thus a greater spatial and racial concentration of delivery costs, in areas with agglomerated freight-related employment and lower household incomes. In the discussion, I offer additional interpretations for this effect.

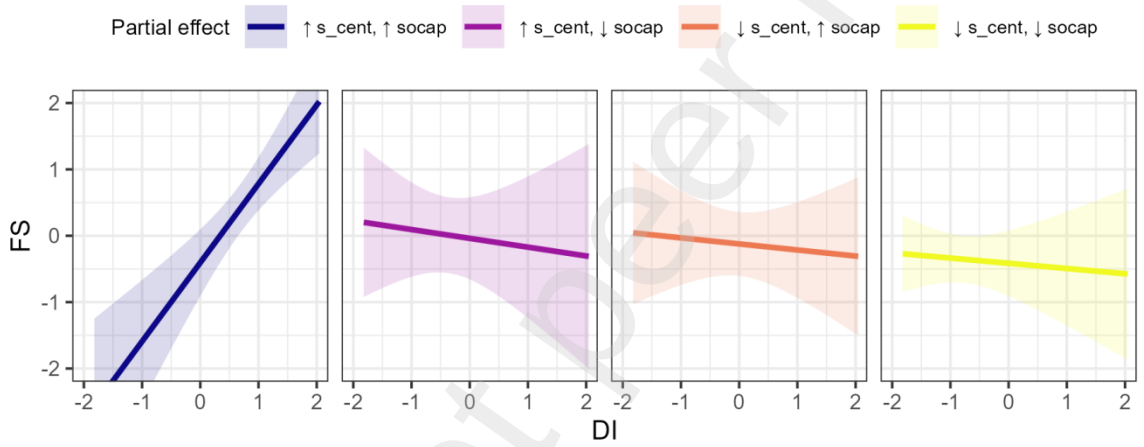

Figure 5: Partial effects of supply centrality and social capital on the relationship between racial segregation (DI) and delivery disparities (FS). NOTE: high (↑) and low (↓) indicate the mean ± one standard deviation.

4.2.2 Demand centrality has significant indirect and total effects

Demand centrality (*d_cent*) has a significantly positive, indirect and total effect on observed racial disparities in last-mile delivery. This finding suggests that logistically compact service areas tend to be fairer, *albeit modestly*, but the above endogenous relationship mediate and condition the impact. I discuss the implications, caveats, and limitations in the following section.

5. Discussion & Conclusion

This study examines the direct and indirect effects of supply and demand centrality—determinants of logistics sprawl—on racially disparate externalities generated by last-mile delivery in 39 MSAs. POC are disproportionately exposed to delivery costs in nearly every observed MSA. However, the degree of (un)fairness varies considerably across service areas: POC experience cost-exposure levels as high as 3.7-times their ordering share and as low as 0.3. But what explains this variation, and how might policy reduce racial inequities in urban freight?

As expected, sprawling urban form, decentralized supply, and high racial segregation are associated with disparate delivery costs. Results echo the findings of other authors (Ewing et al., 2016), as well as Smart Growth, New Urbanist, and EJ advocates for inclusive land use and transport reform (e.g., Quattro, 2024). Perhaps surprising, however, is the conditional role played by social capital. High social capital is associated with higher disparities, despite some studies finding the contrary (Ataullah et al., 2023), or limited effect (Ard and Fairbrother, 2017; Ewing et al., 2016). The finding may suggest a "dark side" of social capital (Gannon and Roberts, 2020; Schwanen et al., 2015), in which strong social and institutional ties create negative externalities.

One possible explanation is that socio-economically disadvantaged communities or those reliant on freight-intensive sectors for employment expend social capital to encourage LMDS siting, accepting traffic-related disamenities in exchange for perceived economic opportunity (Banzhaf et al., 2019). De Lara (2018) details an example in Moreno Valley (California) where local representatives and developers leveraged concerns of Hispanic labor organizers to fast-track council approval of a W&D (pp. 127-146).[2] In fact, municipalities and polluting industries may frequently position low-wage jobs as a trade-off for local health impacts, a bargain EJ scholars have long-termed "environmental blackmail" (Bullard, 2000). Yet such trade-offs do not always yield the economic benefits they

[2] The author reports, three years after opening, the W&D had yet to fulfill its job creation targets or environmental commitments.

promise. Chapple (2018), for instance, links local fiscalization of greenfield industrial development to wage decline in California.

Information regarding W&D's externalities may have also been less evident to host communities in this study's period of analysis. Fried et al. (2025) find most reported community opposition to W&D occurred after 2020. Before then, economic and environmental concerns may have felt less salient as a basis for contesting W&D. They also find wealthier, single-family jurisdictions enacted many consequent land use restrictions. More advantaged communities may leverage high social capital to block freight-related projects in their neighborhood and redirect siting into disadvantaged neighborhoods, echoing research on exclusionary land use policies and parochial not-in-my-backyard (NIMBY) movements (Scally and Tighe, 2015; Trounstine, 2020).

Finally, results point to an indirect association between proximity logistics—i.e., smaller distances between delivery hubs and demand—and reduced racial disparities. Researchers have proposed many operational strategies to better integrate logistical facilities into high-demand regions, including microhubs (Gunes et al., 2024), parcel lockers, and logistics hotels (Kin et al., 2024). Strategies to make proximity logistics more compatible with surrounding neighborhoods include mixed-use warehouse design, architectural buffering and place-making, and Complete Streets that integrate goods and people mobility (Buldeo Rai, 2024; Conway, 2024; Lane and Rappaport, 2020). Cities should also broaden policies to support EJ and prevent economic displacement (Anguelovski, 2016), given the apparent link between reduced W&D density and gentrification (Qin et al., 2024).

Community benefit agreements (CBAs) offer one path forward by linking logistics development to tangible neighborhood benefits, including local hiring, union protections, vehicle electrification, and investments in housing, transit, or green space (Buldeo Rai, 2023; Fried et al., 2025). However, asymmetrical power dynamics governing community-developer negotiations may also limit the extent to which CBAs fulfill these stipulations. For instance, W&D developments in Detroit (Michigan) did not trigger a CBA mandated by the city's community benefits ordinance, prompting residents to

question the policy's credibility and effectiveness (Saha et al., 2024). Ultimately, mitigating freight's negative externalities (and/or enhancing positive externalities) through community governance requires regulatory planning, enforcement, and accountability.

5.1 Limitations

Similar to broader challenges in the EJ and transport field, variable definitions and measurements can sometimes alter the interpretation of outcomes (Karner et al., 2025; Noonan, 2008). For instance, defining "target" groups, equity indicators, spatial units and joins can influence observed disparities in delivery VMT exposure (see Fried et al., 2024b). This study also relies on static external cost coefficients and secondary indices, such as Ewing & Hamdi's (2014) compactness and Fraser et al.'s (2022) social capital measure, whose validity this study does not independently assess. Future research can enhance robustness through sensitivity analysis of stochastic outcomes, alternative control selections and racial/ethnic group comparisons, and scenario testing.

Another key assumption—that delivery benefits are proportional to the number of deliveries received—also overlooks potential positive externalities that could "even out" observed racial disparities (e.g., job growth, public revenues, faster access to goods). Fried & Garcia (2024) complicate these benefits by showing, for example, access to goods is unevenly distributed and that labor conditions across trucking and warehousing sectors remain poor. Additionally, while the logistics sector may create jobs, it does not require nearby residents to be the ones to work them. Evidence for the spatial mismatch hypothesis is well-established (Blumenberg and Manville, 2004; Kain, 1992), and has evolved into other forms of accessibility and transportation poverty for low-income commuters (Lucas, 2012).

Future studies can operationalize positive freight externalities considering these caveats. However, as Pastor (2004) argues, the "vicious choice" between economic security and physical health may be less a Coasian bargain and more a product of structural power imbalances. It is a choice no community should have to make, and neither does this study.

5.2 Conclusion

To summarize this study's novel contribution, the analysis finds:

- POC are exposed to more delivery external costs despite ordering less than White populations in almost every MSA. This disparity is partially attributable to a spatial and racial mismatch between delivery supply and demand. Smaller distances between supply and demand correlate to a smaller racial disparity in delivery externalities.
- Classical indicators of urban inequality and agglomeration mediate and condition this effect. High racial segregation and social capital accentuate logistics sprawl's disparity-producing impacts.

In other words, existing racial marginalization presents a boundary condition for the equity benefits of a more logistically compact delivery environment.

Despite the corrosion of socio-environmental and anti-racist transport priorities at the national level (Barajas et al., 2025), local and state agencies continue to incorporate environmental and social equity goals into their broader scope of work. This work includes a long-time push toward compact, inclusive, and environmentally sustainable development. Proximity logistics represents an important step toward more equitable urban freight transport and land use. Yet strategies seeking to address environmental injustice in freight must ultimately confront the deeper entanglements of social, political, and economic inequality that shape the urban landscape.

6. Acknowledgements

I would like to thank Drs. Anne Goodchild and Julian D. Marshall for their feedback during earlier versions of this manuscript, as well as for their indelible support throughout my research.

7. Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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