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Measuring Transit Equity of an On Demand Multimodal Transit System

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ABSTRACT

Problem research strategy and findings: On-demand transit is attracting the attention of transportation researchers and transit agencies for its potential to solve the first-mile/last-mile problem. Although on-demand transit has been proved to increase transit accessibility significantly, its impact on transit equity and equality has not been addressed. In this study we examined the potential impact of the On-Demand Multimodal Transit System (ODMTS) in Atlanta (GA), on both transit equity and equality compared with the existing transit system. The results showed that ODMTS could have a positive impact on transit equality by reducing the disparity in transit service between neighborhoods close to and far from the existing transit network; however, it may not improve transit equity.

Takeaway for practice: This study highlights the fact that improving transit service alone is not enough to create an equitable transportation environment, as accessibility is determined by both transportation and land use. Planners should consider interventions that address both factors, such as transit-oriented developments with affordable housing, to meaningfully tackle the inequities in transit accessibility. An interactive online portal for further exploration of various scenarios of accessibility changes in Atlanta and their impact on equity and equality is available at <https://geospatial.gatech.edu/transit-equity>.

Keywords: Transit equity, on-demand transit, microtransit, transit accessibility

The ease of traveling the first and last miles of trips via public transit is a crucial factor in the choice of public transit over other modes of transportation, especially in cities where public transit is not the most favored option, such as Atlanta (GA). A potential solution is a public on-demand transit service that solves the first- and last-mile issue by connecting users' homes and destinations to public transit stops via on-demand shuttles operated by a transit authority.

One such system is the On-Demand Multimodal Transit System (ODMTS), which has been successfully pilot-tested in four Atlanta neighborhoods in collaboration with the Metropolitan Atlanta Rapid Transit Authority (MARTA; Van Hentenryck et al., 2023). ODMTS is considered *multimodal* because it connects the existing public transit network with on-demand shut-

tles to provide first- and last-mile services. In other words, ODMTS integrates high-frequency fixed-route modes of transportation (such as trains or buses) and on-demand shuttles to create a cohesive public transit system designed to optimize riders' journeys from origin to destination. This process typically involves transport by an on-demand shuttle from passengers' origin to a train or bus station, where they then use fixed-route services to traverse longer distances. Another on-demand shuttle facilitates the completion of the trip, ensuring that the first- and last-mile segments are efficiently navigated. Providing ODMTS as a complementary service to the conventional public transit system makes public transit more accessible, which in turn can reduce auto dependency.

Previous studies based on similar pilot programs found that ODMTS improves transit accessibility signifi-

cantly (Bills et al., 2022; Brown et al., 2021; Kang & Hamidi, 2019; Zhang et al., 2022). However, its impact on fostering an equitable transportation environment has largely been unaddressed (Palm et al., 2021). We found only two studies that offered nuanced yet mixed opinions about the equity implications of ODMTS (Bills et al., 2022; Brown et al., 2021). Our study examined how including an extensive, region-wide¹ ODMTS would improve access to public transit for all Atlanta residents, especially those who are transit dependent.

We first measured the accessibility of ODMTS versus current transit services in Atlanta using a cumulative opportunities measure that counted the number of opportunities (in this case, jobs) that can be reached within a certain temporal threshold. Whereas most previous studies considered only travel time, we used an additional threshold: the ratio of public transit travel time to driving travel time. That is, we assessed how many destinations one can access within a given time and how quickly one can get there on public transit compared with driving. We call the former *absolute* accessibility and the latter *relative* accessibility.

We then measured the distribution of transit accessibility across the study area based on principles of equity and equality. *Equality* refers to the even distribution of resources among all communities. *Equity* acknowledges that individuals in different communities have varying circumstances and demands, requiring resource allocation to be focused where the need is greatest. Both concepts have been reported in studies examining fairness in the distribution of transportation investments. A widely held view on equity and equality is that although the two sometimes conflict, they can be complementary and achieved together in a well-designed system. We measured transit equity by estimating the overall gap between transit supply (the two types of transit accessibility) and transit demand in each neighborhood. Transit equality was measured by the Gini coefficient and Lorenz curve, which are common measures of statistical dispersion or inequality.

Here, we compare the ODMTS-supported transit system with the current system based on the above analyses and discuss the equity and equality implications. The findings from this study will improve the discourse on the distributive justice of on-demand transit systems.

Literature Review

Transit Accessibility

Transportation equity, measured primarily by accessibility, reflects how a transportation system facilitates the reaching of destinations quickly and comfortably. However, detailed definitions and measures of accessibility vary (Handy, 2002; Schoon et al., 1999), and the

topic is debated (Malekzadeh & Chung, 2020). Geurs and van Wee (2004) identified four core accessibility components: land use, transportation, temporal, and individual. Land use involves opportunities available at destinations such as jobs or stores, whereas transportation denotes travel options. Temporal aspects involve the time-specific availability of opportunities and transport options. The individual component encompasses the traveler's characteristics, including desires and abilities. These components interact with one another; thus, ideally, accessibility measures should consider all four components (Geurs & van Wee, 2004).

Handy and Niemeier (1997) categorized measures of accessibility as cumulative opportunities and gravity and utility-based measures. Cumulative opportunities count the number of reachable opportunities within a travel time limit, offering intuitive understanding. Gravity-based measures weight opportunities by travel time or cost, and utility-based measures use a random utility model, expressed as a multinomial logit model. Although it is complicated, the utility-based measure has theoretical and empirical advantages (Handy & Niemeier, 1997). All three measures have been widely used in the literature (Malekzadeh & Chung, 2020). We used the cumulative opportunities measure.

The literature has distinguished between positive and normative accessibility measurements (Paez et al., 2012). Positive measures focus on individuals' travel behaviors, highlighting their inherent variability. Normative measures focus on the theoretical impacts of transportation services, often using quantifiable metrics such as opportunities within a fixed threshold. Such normative measures are invaluable when gauging the potential impacts of hypothetical or newly proposed services within predefined travel parameters.

Another distinction is between people-based and place-based measures. Whereas people-based measures offer insights into individual travelers' diverse preferences and behaviors, place-based measures focus on the accessibility potential of defined zones, providing an overview of a location's access potential (Siddiq & Taylor, 2021). Such an approach accentuates the importance of certain areas that need special attention without the detailed consideration of individualized preferences and choices.

Evaluating the accessibility of a public transit system requires information about not only the service network's extent but also the frequency and reliability of service to reflect its schedule-dependent characteristics. The emergence of General Transit Feed Specification (GTFS) made it easier to access such information. GTFS provides detailed public transit schedules and geolocation data accessible via an application programming interface (API). Several studies have used GTFS data to develop equity measures of public transit.

Studies using GTFS data include Karner's (2018) assessment of job accessibility and transit service equity based on income levels, Owen and Levinson's (2015) investigation of job accessibility through travel time variations, and Farber et al.'s (2014) identification of food deserts by measuring accessibility to supermarkets.

Transit Equity and Equality

Social justice pertains to both equity and equality, with both concepts based on a fair distribution of public resources, such as public transit services. Many transportation studies have treated equality as one of the equity standards (Bertolaccini & Lownes, 2013; Carleton & Porter, 2018; Delbosc & Currie, 2011; Welch & Mishra, 2013). However, our study makes a clear distinction between the two.

First, the concept of equality suggests that everyone has equal rights, so resources should be distributed evenly, regardless of individual differences. Equality is perceived as the fundamental criterion for distributive justice (Martens et al., 2012). Unless a convincing argument supports deviation from equal distribution, equality should be deemed the only reasonable way to distribute resources among people (Smith, 1994). The Gini coefficient and Lorenz curve, common measures of statistical dispersion, are often used to represent the level of inequality within a population or group. For instance, Delbosc and Currie (2011) used these measures to analyze the distribution of transit services in Melbourne (Australia). Their results showed a Gini coefficient of 0.68 for the overall population, indicating severe inequality. In addition, the Lorenz curve revealed that 70% of the population shared only 19% of the transit services, whereas the remaining 30% shared 81%.

From an equity perspective, however, deviation from equality can be justified by the fact that the demand for resources varies among individuals or groups. Equity considers individual differences and aims to distribute resources in a way that balances unequal advantages or disadvantages. Ignoring differences in transit needs during planning can have negative consequences (Palm et al., 2021). For instance, access to private vehicles and public transit has been positively correlated with an individual's likelihood of obtaining and maintaining employment (Blumenberg & Pierce, 2014b). Moreover, a study by Ma et al. (2018) found that transport-disadvantaged populations—those with limited or no access to cars—were associated with worse physical or mental health and lower levels of subjective wellbeing. In essence, the transportation system can significantly moderate social exclusion, highlighting the importance of equity in transportation projects.

The literature has introduced two approaches to transit equity: horizontal and vertical. Horizontal equity,

rooted in egalitarianism, aims for an equal distribution of resources among equally situated individuals (Litman, 2021; Pereira et al., 2017). Fan and Li (2019) and Jiao (2017) exemplified this approach by estimating transit service gaps using transit-dependent population density as a key variable. The transit-dependent population typically includes nondrivers and those without access to cars.

Conversely, vertical equity, grounded in social justice, prioritizes transit services for vulnerable social and economic groups to mitigate broader inequalities (Litman, 2021). Carleton and Porter (2018) analyzed transit needs from this perspective, incorporating variables such as the presence of elderly individuals, children, linguistic isolation, a non-White population, low-income households, and households without cars. Similarly, Fransen et al. (2015) used variables that included the presence of elderly individuals, children, unemployed individuals, carless households, subsistence money recipients, and accessibility to primary facilities.

In theory, equity and equality can be achieved together in a distributive justice system (Sen, 2009), although it is challenging to balance them in practice. Rawls (1971) argued that justice requires both the principle of equal basic liberties and the *difference principle*, which ensures that social and economic inequalities are allocated to the greatest benefit of the least advantaged (also known as the *maximin principle*). Rawls's approach recognized the importance of both equality and equity in establishing a just society and sought to balance these concepts through a complex system of normative principles. Although it has not been actively discussed among transportation scholars, balancing the two concepts is also essential in transportation planning because transportation is a fundamental aspect of everyday life and plays a crucial role in enabling people to participate in social, economic, and cultural activities.

In the Atlanta metropolitan region, the goal of transportation equity has remained elusive (Bullard et al., 2000; Henderson, 2006; Karner & Duckworth, 2019). Atlanta's history of racial segregation is imprinted on its social geography, evidenced by a stark distinction in the racial composition of the northern suburbs compared with the southern metro counties. When the MARTA system was designed in the 1960s and 1970s, the region's White suburban counties in the north rejected the idea of funding transit with a 1% sales tax; as a result, the transit system was concentrated in the majority-Black city of Atlanta (Karner & Duckworth, 2019). Although racial concentrations have declined with population growth in most counties, the MARTA system has remained mostly unchanged since its inception. In addition, new employment centers have cropped up in the northern suburbs with high concentrations of White residents, exacerbating the problem of

job access for poorer residents in the city. The spatial mismatch between jobs and housing and its implications for poor minority communities remain a concern in Atlanta (Abramson et al., 1995; Ihlanfeldt, 1994; Kain, 1968). Augmenting the current MARTA system with ODMTS may alleviate historical inequities and expand economic opportunities for disadvantaged communities.

Equity and Equality Implications of On Demand Transit

Trips via public transit generally consist of three legs: 1) an access leg from an origin location to a nearby transit stop, 2) a transit leg from the origin transit stop to a destination transit stop, and 3) an egress leg from the transit stop to a destination. Most users of public transit accomplish the first and last legs by walking, which often takes more time than the second leg (waiting time and in-vehicle time on public transit combined). This intrinsic difficulty in connecting transit users from their origins and destinations to transit stops, called the *first-mile/last-mile problem*, has limited the accessibility and convenience of public transit systems.

With recent innovations in technology, researchers have explored various potential solutions for the first-mile/last-mile problem: shared bikes, e-scooters, and other types of micromobility (Fan et al., 2019; Grosshuesch, 2019; Liu & Miller, 2022; McQueen & Clifton, 2022; Mitra & Schofield, 2019; Zuniga-Garcia et al., 2022); autonomous vehicles (Chen et al., 2020; Gurumurthy & Kockelman, 2020; Huang et al., 2021; Moorthy et al., 2017; Shen et al., 2018; Thorhauge et al., 2022); and on-demand transit (Bürstlein et al., 2021; Grahn et al., 2022; Martin et al., 2021).

Existing studies of on-demand transit have agreed on its improvement of overall accessibility (Bills et al., 2022; Brown et al., 2021; Kang & Hamidi, 2019), particularly at night (Zhang et al., 2022). For example, Kang and Hamidi (2019) found that on-demand transit can save 5 to 10 min in travel time, which can significantly improve job accessibility using public transit. However, most research has not explicitly measured the impact on equity or equality (Palm et al., 2021); only a few studies had mixed opinions. Bills et al. (2022) found that accessibility gains from on-demand transit would be higher for lower-income, transit-dependent neighborhoods, suggesting that on-demand transit can reduce the gap between the advantaged and disadvantaged. Conversely, Brown et al. (2021) pointed out that on-demand transit does not increase accessibility for marginalized populations, which might be correlated with access to technology. No analysis of the effect on equality was performed.

Methods and Data

Study Area

The study area included three counties surrounding Atlanta: DeKalb, Fulton, and Clayton. Home to approximately 2 million people, this area accounts for almost half the population of Metro Atlanta, the most populous metropolitan statistical area in the state of Georgia. MARTA currently operates local bus and train services within the study area (Figure 1 shows MARTA operations), whereas Xpress provides a regional commuter coach service for counties around Atlanta. MARTA's rail network comprises 38 stations across four lines. MARTA also operates more than 500 buses on more than 110 distinct lines. Nevertheless, 5-year data from the 2019 American Community Survey (ACS) revealed that the area has a relatively low transit modal share of commuter trips compared with other major cities: The public transit mode share was around 7%, whereas driving alone dominated at 72%. A primary reason for this discrepancy is that the public transit network is not densely distributed, hindering convenient access for a large population (Aquad et al., 2021).

Transit Accessibility Metric

To measure transit equity, we first needed to measure transit accessibility at the neighborhood level. In this study we used the cumulative opportunities measure, which counts the number of opportunities accessible within a certain threshold. We chose this measure for its simplicity. One important consideration when deciding how to measure accessibility (and thus equity) is the ease of interpretation and communication of the results to readers; a simple, intuitive measure such as cumulative opportunities has that advantage. Although gravity-based measures are often considered more accurate, Kapatsila et al. (2023) found that they can be replaced by cumulative opportunities measures, particularly when calculating the mean travel time of a region.

Transit accessibility in this study was defined as how many destinations one can reach by public transit within a given threshold. We used two types of thresholds: 1) time (number of minutes) or 2) ratio of public transit time to driving time. To distinguish the two, we refer to the first as *absolute accessibility* and the second as *relative accessibility*. Relative accessibility evaluates how attractive public transit is compared with driving. Some studies have compared travel time by public transit with travel time by driving (Klumpenhouwer et al., 2021; Transit Capacity and Quality of Service Manual [TCQSM], 2013). For instance, TCQSM (2013) used the public transit–auto travel time ratio to understand the decision to choose public transit over driving an automobile. However, no accessibility study has used the ratio as a threshold. Both absolute and relative

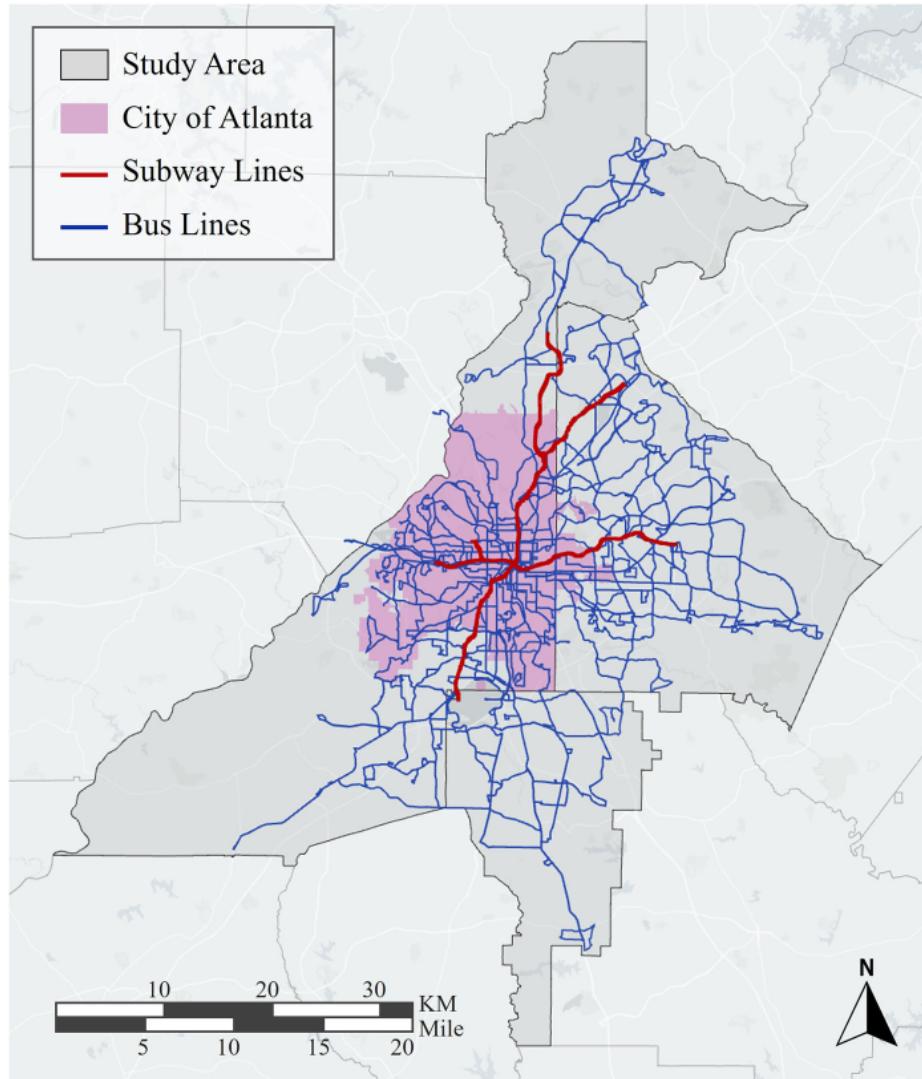


Figure 1. Public transit network in the study area.

accessibilities are important when people choose public transit as a mode of transportation. Our analysis is based on three counties around Atlanta: Fulton, DeKalb, and Clayton. The geographic unit of analysis is the census block group (BG); there were 1,060 BGs in the study area.

Operationally, we calculated a given BG's transit accessibility by a weighted average of the accessibility measure (either absolute or relative) between the BG centroid and all other BG centroids. We were interested in measuring the transit accessibility of commuting trips.² Thus, the index measured the proportion of people residing in a given BG who could reach their workplace by public transit within a given threshold.

Absolute accessibility was based on a time threshold T . The accessibility index ranged from 0 to 1: For example, an accessibility index of 0.5 means that 50% of people in a given BG can reach their workplace by public transit within threshold T . Relative accessibility was based on a ratio threshold R . For instance, if the value of

threshold R is 3, the index indicates the proportion of people in a given BG who can reach their workplace by public transit within three times the amount of driving time required. See the [Technical Appendix](#) for formulae and detailed descriptions of the accessibility measures.

We exercised caution in choosing the threshold values, as they could be perceived as defining a sufficient level of accessibility that cannot be universally agreed on (Martens, 2016; Paez et al., 2012; Pereira et al., 2017). Studies typically choose 30 or 45 min as the threshold T (Ermagun & Tilahun, 2020; Klumpenhouwer et al., 2021; Palm et al., 2021), but discussions of the value of threshold R are notably absent.

We based the thresholds on mean travel time in the study area, in line with Kapatsila et al. (2023), who asserted that calculating cumulative opportunities using the study region's mean travel time yields relatively accurate results. We used the mean commuting travel time by mode from the 2019 ACS 5-year data to determine the values of T and R . The average travel time for

private vehicles (driving alone) was 29.6 min, and for public transit it was 56.0 min. The ratio between these times was approximately 1.9. Thus, we selected 60 (minutes) and 2 (twice driving time) as the values for T and R , respectively. These figures align with the TCQSM (2013), which suggested that a public transit trip 16 to 30 min longer than the equivalent car trip is acceptable to riders.

In addition, we tested various values of the thresholds T and R to examine the sensitivity of the output measures. We found that the trend in the output measures was largely consistent over various threshold values. We discuss the sensitivity of transit accessibility in the Results section. The sensitivity of equity and equality measures can be found in the [Technical Appendix](#).

Data required for this analysis were 1) travel time by the current transit system between every pair of BGs, 2) travel time by ODMTS between every pair of BGs, 3) travel time by driving between every pair of BGs, and 4) number of commuters between every BG pair.

We assumed that the first and last miles of trips on the current transit system were accomplished by walking (i.e., a trip consisted of walking, riding on public transit, and then walking). A walking trip was simulated by a network simulation using an A-star shortest path search algorithm. Public transit travel time between transit stops was obtained using the R package “tidytransit” and GTFS data provided by MARTA and Xpress. Because we did not know which transit stop the traveler would use, we selected 100 stops near the origin and 100 stops near the destination, compared 10,000 (100×100) possible public transit trips, and selected the one optimal trip that minimized the total travel time (walking + transit + walking). In addition, to account for the frequency of transit service, we simulated a trip at 5-min intervals from 6 a.m. to 10 p.m. and then calculated the daily average value, including the average waiting time for transit service.

Travel time by ODMTS was obtained by simulation. In the ODMTS trip, the on-demand shuttle could serve the first and/or last mile of the trip, or it could cover the whole trip if the travel distance was short, which was decided by the simulation algorithm. The simulation provided the in-vehicle travel time of the shuttle and the train or bus and the waiting time for the train or bus, considering the traffic and transit operating conditions. In our study, the simulation was based on the assumption that the trips were made during the morning peak hours. In addition, we set the following assumptions: 5 min of initial on-demand shuttle waiting time, 1 min of second shuttle waiting time, 1 min of shuttle-to-bus transfer time, and 3 min of shuttle-to-rail transfer time. Assumptions of shuttle waiting time were informed by findings from the real-time simulation by Auad et al. (2021). The shuttle-to-bus and shuttle-to-rail

transfer times did not include waiting times; they referred to the time required for a user to exit the shuttle and walk to either the bus stop or the train platform. Assuming the shuttle stopped directly in front of a bus stop or train station, the assumptions of 1 min and 3 min, respectively, were considered generous.

We gathered data on driving time using Bing Maps Routes API. The number of commuters between BGs was obtained from the Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics.

Transit Equity and Equality Metrics

Based on the transit accessibility index measured at the BG level, we evaluated how fairly transit services were distributed using two measures: equity and equality.

Transit equity was measured by the transit service gap index, or the gap between transit supply (the two types of transit accessibility) and transit demand: the higher the value, the more inequitable the transit service. The formula for the transit gap index can be found in the [Technical Appendix](#). The index ranges from 0 to 1: if the overall gap between transit demand and supply is large, the value is close to 1. We selected the following seven transit demand-related variables based on existing studies: 1) population without vehicles, 2) minority population, 3) low-income population, 4) unemployed population, 5) disabled population, 6) elderly older than 70, and 7) children younger than 14. All seven variables were sourced from U.S. Census 2019 ACS 5-year estimates. Although some previous studies used a composite index by aggregating the various demand variables, the composite measure may mask or misrepresent the level of inequity among various disadvantaged populations (Brick, 2015; Carleton & Porter, 2018; Delbosc & Currie, 2011; Jacques et al., 2013). Thus, we measured separate gap indices for each transit demand variable. Because there are two types of transit accessibility and seven types of transit demand variables, we obtained 14 transit gap indices.

Figure 2 shows one of the demand variables—percentage of the population without vehicles—providing the context of the study area. The map illustrates that neighborhoods with a high number of transit-dependent households were predominantly within the city boundary, where the existing transit system offers better service.

Transit equality was measured by the Gini coefficient and Lorenz curve. Unlike the measure of transit equity, the Gini coefficient does not reflect transit demand, as it measures the equal distribution of supply. The Gini coefficient ranges from 0 to 1, where 0 means perfect equality: if every BG had the same amount of transit accessibility, the Gini coefficient would be 0. The

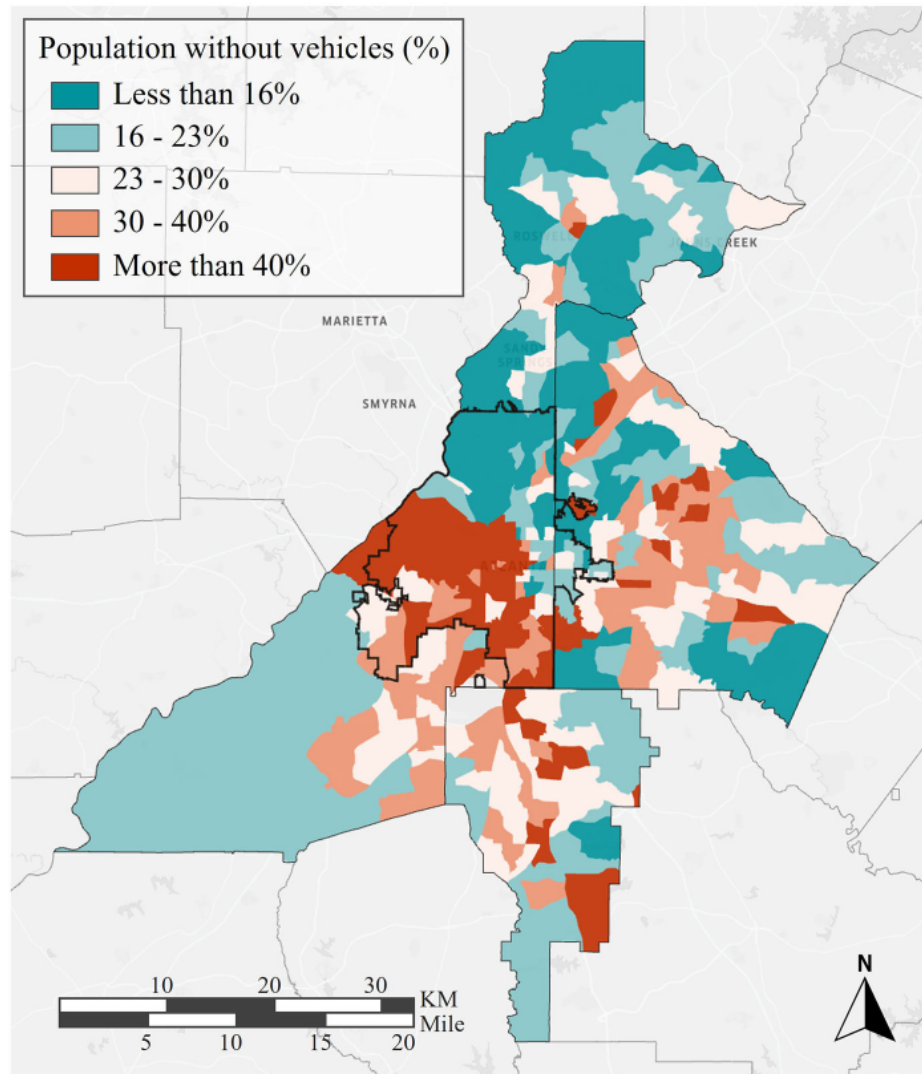


Figure 2. Spatial distribution of the percentage of households without vehicles.

formula for the Gini coefficient is included in the [Technical Appendix](#).

The Lorenz curve is a graphic representation of the Gini coefficient. Figure 3 illustrates a Lorenz curve of transit accessibility distribution among BGs. The dashed line—the line of equality—represents a perfectly equitable distribution. The solid curved line—the Lorenz curve—shows the relative distribution of transit accessibility among BGs. The area between the line of equality and the Lorenz curve, marked A in Figure 3, indicates the overall degree of inequality. The Gini coefficient can be measured by the areas marked A and B: $G = A / (A + B)$ (or $G = 2A$ since $A + B = 0.5$).

The methodology of this study had several limitations. First, we assumed homogeneity within census BGs, which might mask finer-grained disparities in transit accessibility. Second, reliance on 2019 ACS data limited our ability to reflect more recent changes in commuting patterns, especially those influenced by the COVID-19 pandemic. Last, the first- and last-mile travel

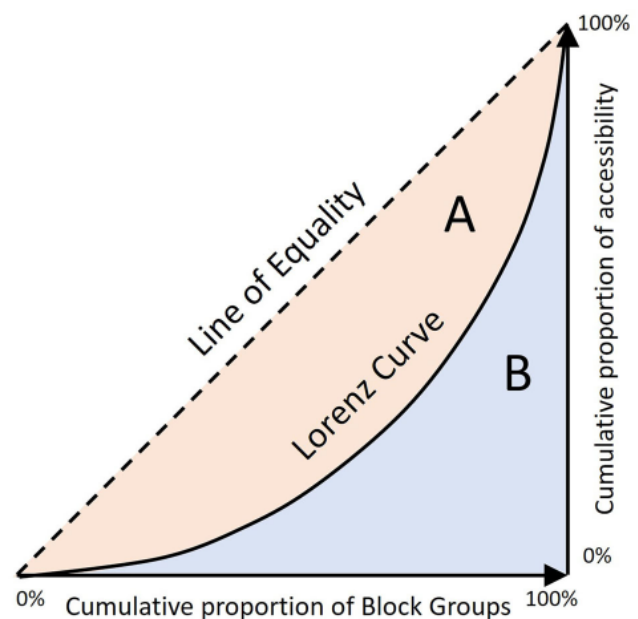


Figure 3. Illustration of Lorenz curve.

assumptions and the simulation models might not fully encapsulate the complexities and variabilities of real-world transit usage. These limitations highlight the need for cautious interpretation of the findings and underscore the potential for additional research incorporating more dynamic and granular data.

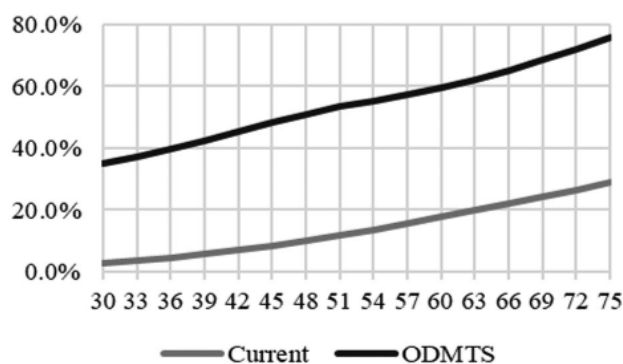
Results

Impact of ODMTS on Transit Accessibility

Figure 4 shows the absolute and relative accessibility of 1) the current transit system and 2) ODMTS. The x-axis indicates the threshold value: time T on the left and ratio R on the right. The y-axis represents transit accessibility. As the threshold value increased, accessibility increased. In both types of accessibility, ODMTS showed significant improvements compared with the current transit system. The ODMTS was 30% to 50% better than the current transit system in terms of absolute accessibility. The difference was more evident in the relative accessibility graph: As the threshold value increased, the relative accessibility of ODMTS got closer to 100%, whereas that of the current transit system never reached 30%.

Figure 5 compares the absolute accessibility of the current transit system and ODMTS when the time threshold value was 60 min. Although most neighborhoods showed very poor transit accessibility (less than 5%) with the current transit system, ODMTS greatly improved overall accessibility, so that even the least accessible neighborhood's absolute accessibility was greater than 20%.

Figure 6 compares the relative accessibility of the current transit system and ODMTS when the ratio threshold value is two times driving time. The improvement here is even more evident than in Figure 5. In the current transit system, whereas absolute transit accessibility was relatively high near the city center, relative transit accessibility was high along the transit network lines. In ODMTS, public transit became a very competitive mode of transportation in most neighborhoods.



Impact of ODMTS on Transit Equity

Before measuring the transit gap index, we examined scatterplots of seven transit demand variables (on the x-axis) and two types of transit accessibility (on the y-axis) at the BG level. As explained in the Methods and Data section, we selected a specific threshold value for each type of accessibility: 60 min for absolute accessibility and two times driving time for relative accessibility. In Figure 7, the trend lines in each plot indicate the transit gap index: An upward slope of the trend line indicates the distribution is equitable. In several cases, the current transit system showed a greater positive slope than ODMTS, implying that ODMTS would make the transit service inequitable.

The results of measuring the transit gap index, shown in Figures 8 and 9, confirmed our observation from the scatterplots in Figure 7: ODMTS did not lead to any improvement in transit equity. Given that transit demand was one of the factors considered in optimizing the ODMTS network, these results are puzzling.

Impact of ODMTS on Transit Equality

Figure 10 illustrates the Gini coefficients based on absolute and relative accessibility. The figure shows noticeable differences between the current transit system and ODMTS: the Gini coefficients of ODMTS (0.18 and 0.16) were much lower than those of the current transit system (0.53 and 0.87), meaning that ODMTS would improve transit service for most people.

In addition, the differences in the Gini coefficients were much greater for relative accessibility than absolute accessibility: When switching from absolute accessibility to relative accessibility, the Gini coefficient of the current transit system increased (from 0.53 to 0.87), but that of ODMTS decreased (from 0.18 to 0.16). This means that even if we measured accessibility based on the ratio of transit travel time to driving time, accessibility of the current transit system would still be significantly affected by proximity to the transit network. In other words, in areas that were distant from the

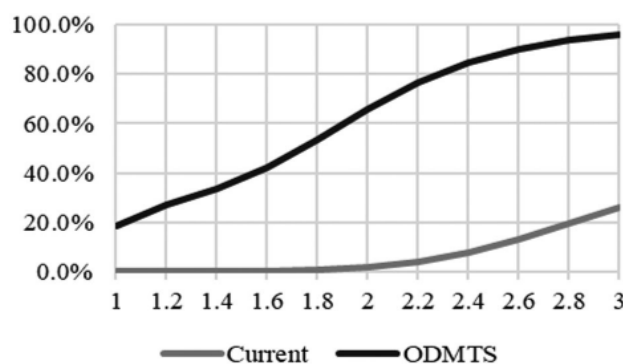


Figure 4. Absolute (left) and relative (right) accessibility of ODMTS and the current transit system. The x-axis represents each threshold value: time (left) and ratio (right); the y-axis indicates the accessibility of each transportation system.

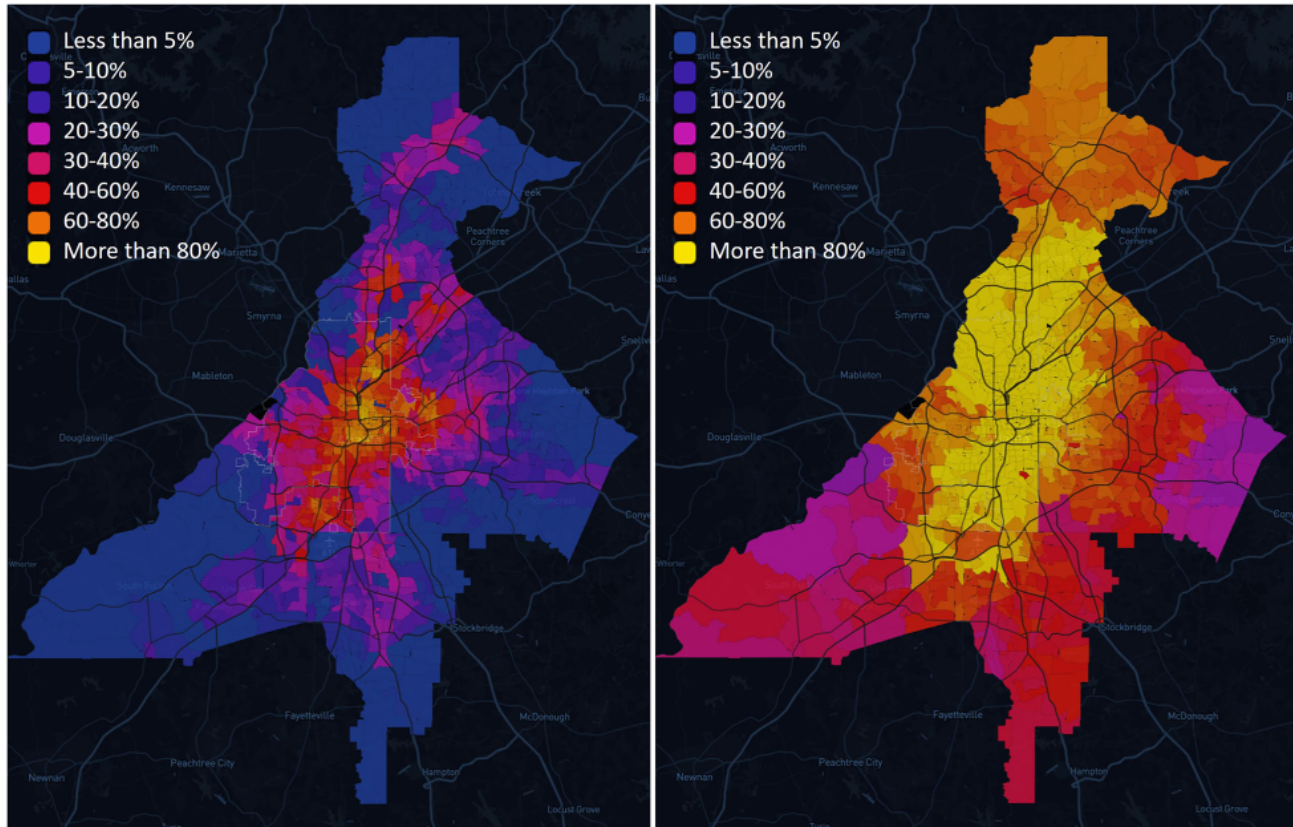


Figure 5. Absolute accessibility of the current transit system (left) and ODMTS (right) at the time threshold of 60 min.

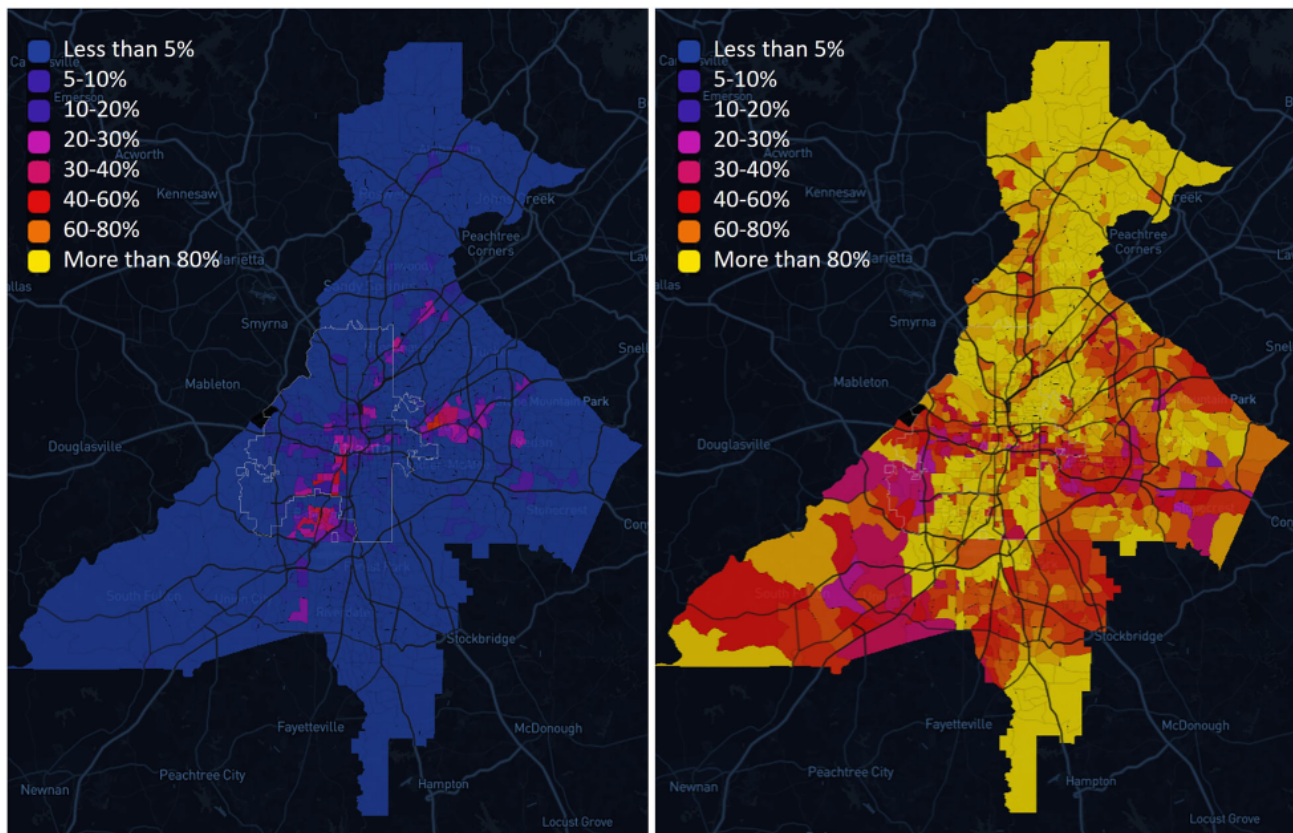


Figure 6. Relative accessibility of the current transit system (left) and ODMTS (right) at the ratio threshold of 2 (twice driving time).

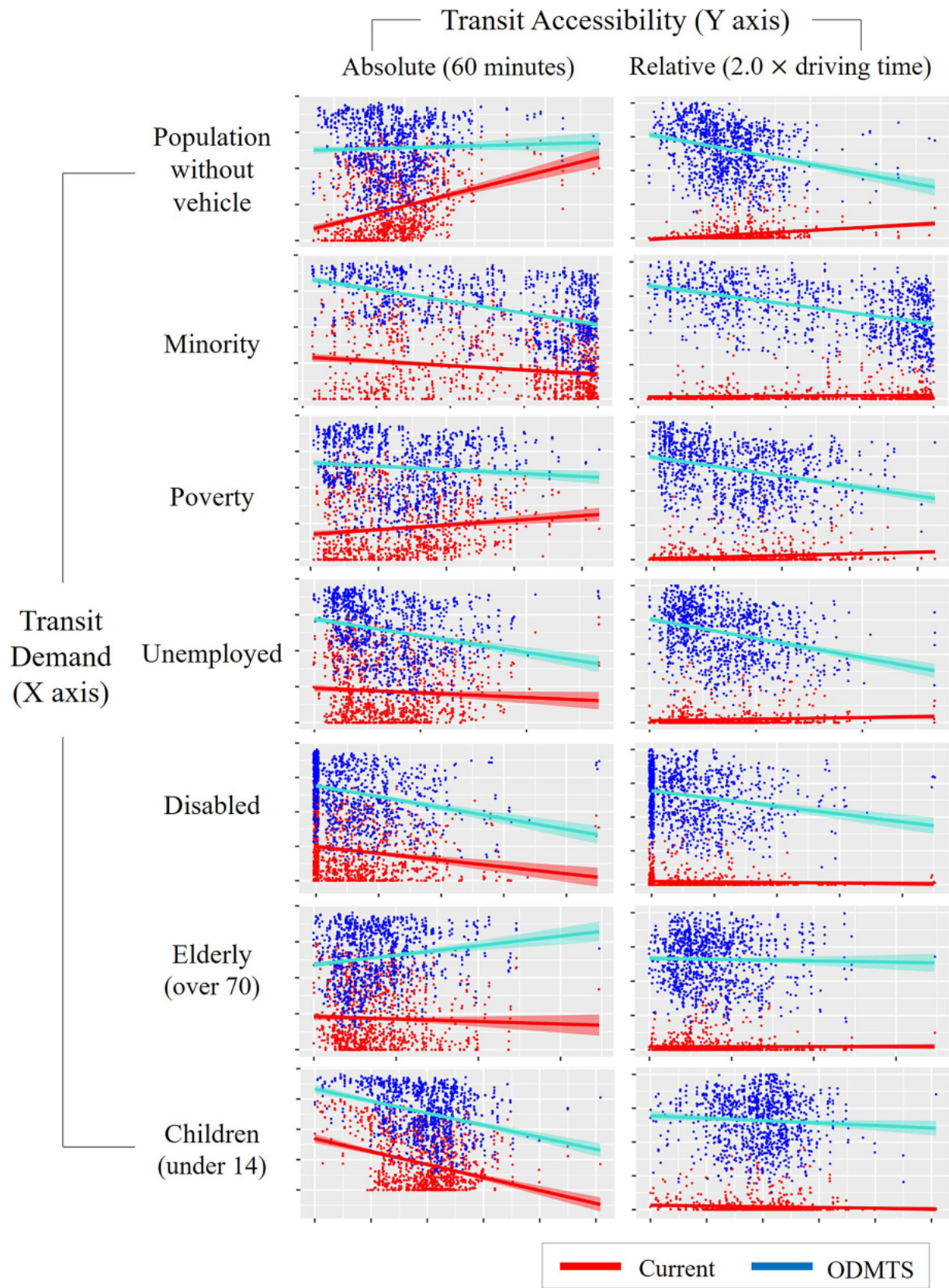


Figure 7. Scatterplots of seven transit demand variables (x-axis) and two types of transit accessibility (y-axis) at the BG level. An upward trend line indicates equitable distribution.

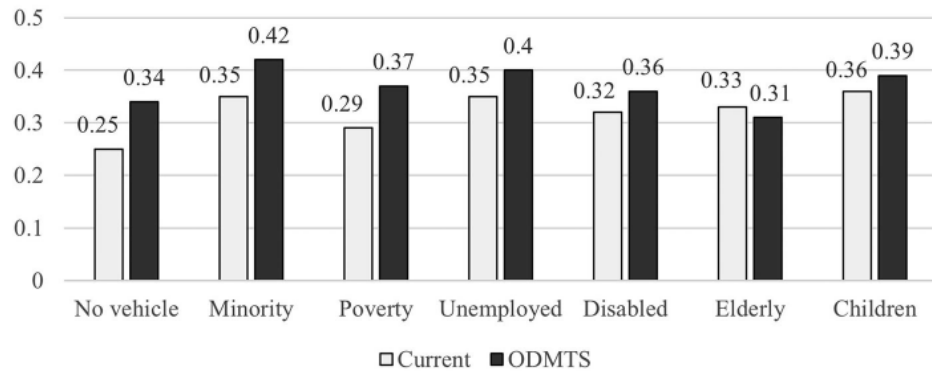


Figure 8. Transit gap index based on absolute accessibility of the current transit system and ODMTS.

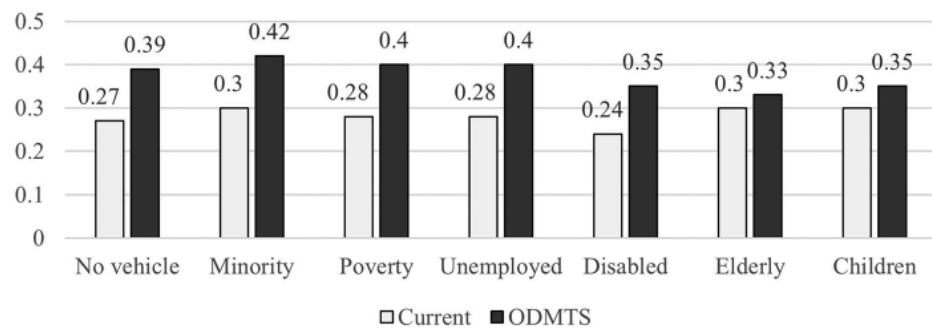


Figure 9. Transit gap index based on relative accessibility of the current transit system and ODMTS.

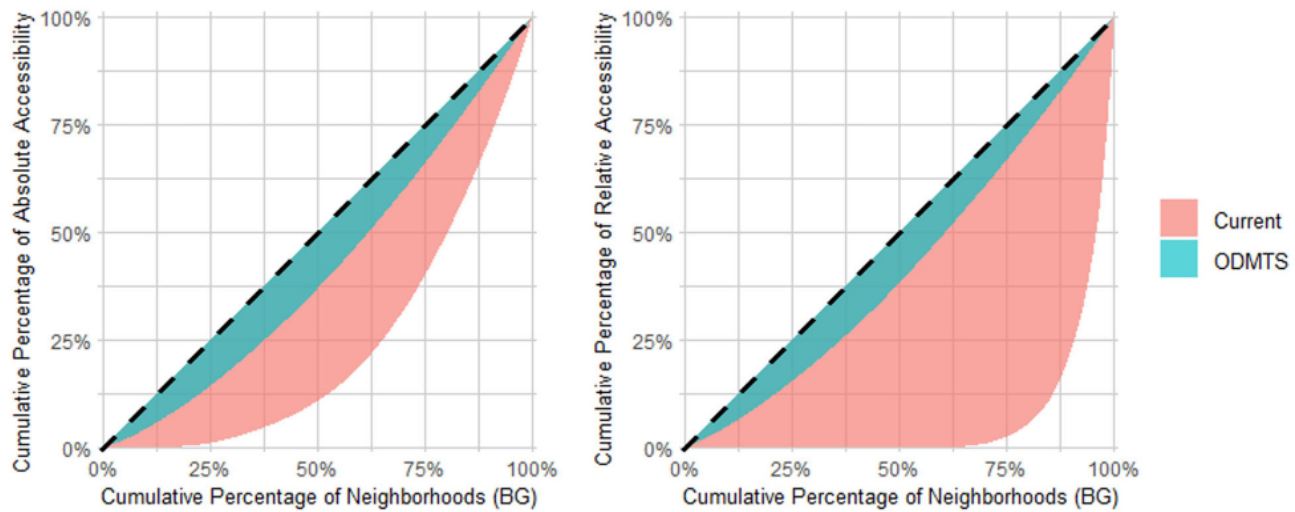


Figure 10. Lorenz curve of absolute (left) and relative (right) transit accessibility: current transit system versus ODMTS.

Table 1. Gini coefficients of absolute and relative accessibility: Current transit system versus ODMTS.

	Current transit system	ODMTS
Absolute accessibility	0.53	0.18
Relative accessibility	0.87	0.16

conventional transit network, public transit was a less attractive option than driving. However, in ODMTS, proximity to the conventional transit network was not as crucial because the shuttles solved the first-mile/last-

mile problem, making public transit a relatively attractive option even in distant neighborhoods. In conclusion, ODMTS can considerably improve the equality of transit service (Table 1).

Discussion

Our assessment of the equity and equality of the simulated ODMTS in Atlanta offered some unexpected results. Although we expected ODMTS to advance both equity and equality, we found that it expanded equality

without improving equity. This result led us to conduct additional investigations into the drivers of equity for the current transit system compared with the one augmented by ODMTS. We found that the distribution of destinations accessed by residents in different parts of the metro region was the primary reason for the divergence of equity and equality results. We knew that transit-dependent populations were more likely to reside close to the city center, as indicated by Figure 2. Therefore, people with high transit demand were currently benefiting more from the existing transit system than people with low transit demand.

Our analysis also showed that average distances to jobs were highest in BGs containing high concentrations of people with high demand for transit. This issue became evident when we divided BGs into three groups based on each transit demand variable and compared each group's average commuting distances, as shown in Figure 11. For all seven transit demand variables, the average commuting distance was greater in neighborhoods with high transit demand.³ Because transit accessibility is about how many destinations can be reached by public transit within a given time, it depends not only on the quality of the transit service but also on the proximity to destinations. For example, a neighborhood with good transit service may not have great transit accessibility if desired destinations are far away.

Our investigation suggests that individuals with high transit demand were better served by the *existing transit system* when accessing all destinations *compared with a typical resident*. As a result, the transit gap was lower for this group than for most of the population,

which was minimally served by the limited and centrally concentrated transit service. ODMTS would extend transit service widely to those who previously did not have access. Therefore, those farther away from the existing system benefited most from increased accessibility to destinations through ODMTS. The spatial distribution of destinations, which, on average, were closer to the group with lower transit demand, became much more accessible to them via public transit. Although ODMTS also improved the transit environment for the group with high transit demand, the enhancement in transit accessibility was lower due to longer average distances to destinations.

These findings indicate that the improvement of transit service alone cannot create an equitable transportation environment, which highlights the fact that accessibility is a function of both transportation and land use (Klumpenhauer et al., 2021; Tilahun & Fan, 2014). We need to consider both factors together to create a truly equitable transportation environment. Compared with improving transportation, intervening in land use is more complicated and challenging because it requires altering the physical landscape and making huge investments in infrastructure (van Wee, 2002). However, changes in the transportation infrastructure, such as ODMTS, can improve market conditions to favor more destinations closer to those with high transit demand. In addition, zoning and building regulation updates can encourage mixed-use developments at higher densities in BGs with high transit demand. One effective planning intervention to address inequities in both transportation and land use is transit-oriented development (TOD) along with sufficient affordable

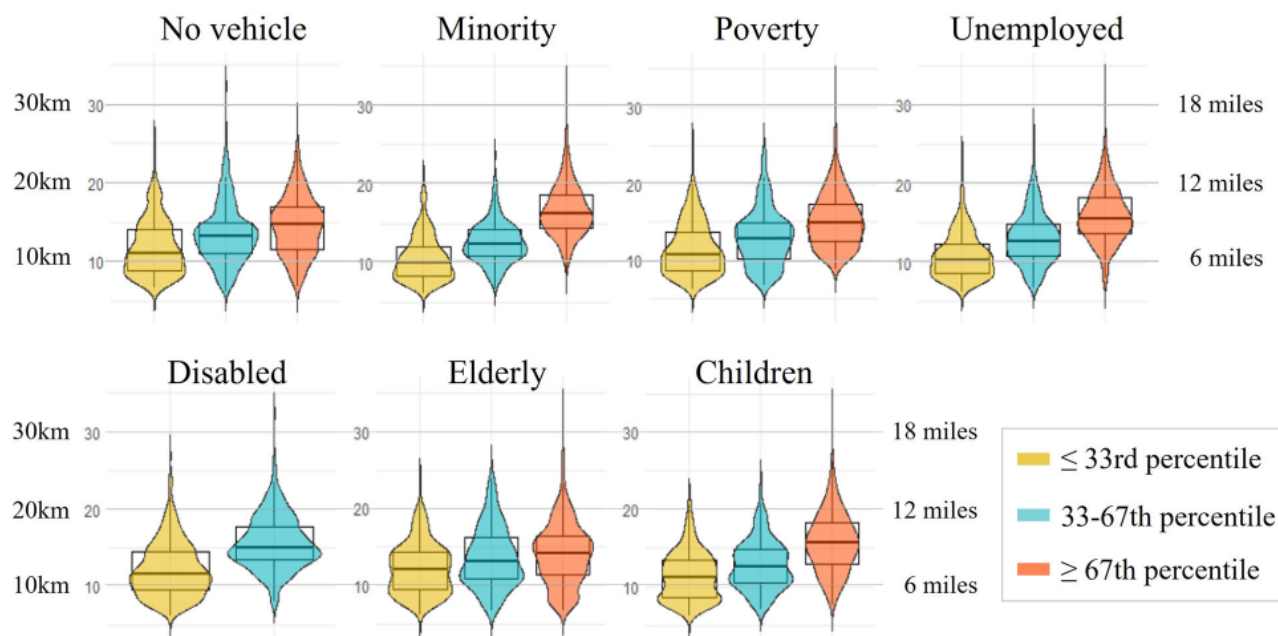


Figure 11. Average commuting distance of low-, mid-, and high-demand groups by each transit demand variable.

housing. TOD involves development near transit stations and corridors to provide easy access to public transit, which also helps create walkable, mixed-use communities. By leveraging affordable housing, TOD can provide low-income households with better transit accessibility, which makes cities more equitable (Pendall et al., 2012; Welch, 2013).

Finally, the outcome of this investigation begs the question: Should cities such as Atlanta invest in ODMTS? Our answer is firmly positive, based on the goals of advancing sustainability, reducing climate-altering greenhouse gases, and moving toward transit equity. By offering an efficient and cost-effective alternative to private automobiles, ODMTS makes public transportation more attractive, thereby reducing fossil fuel use. We also expect cities to adjust regulations and incentives for transforming land use to help advance an equitable distribution of jobs and other destinations. In other words, our static analysis of the current state compared with the future state without accounting for the dynamics of land use may be offering an incomplete picture of the equity impacts of ODMTS, which could evolve in a positive direction over time.

Conclusions

We investigated the impact of ODMTS, a new public on-demand transit system planned in Atlanta, on the fairness of transit service compared with the existing transit system. We first assessed the transit accessibility of both ODMTS and the current transit system using a cumulative opportunities measure that calculated the number of opportunities reachable within two thresholds: travel time (absolute accessibility) and ratio of transit travel time to driving time (relative accessibility). Finally, based on the measured accessibility by neighborhood, we evaluated transit equity (using the transit supply-demand gap index) and transit equality (using the Gini coefficient and Lorenz curve) in the study area. The analyses provided us with the following meaningful findings.

First, the results showed that ODMTS did not improve transit equity. Out of the 14 transit gap indices (based on two transit accessibilities and seven transit demand variables), 13 indices were higher in ODMTS than in the current transit system, which means ODMTS was more inequitable. To make sense of this unexpected result, we hypothesized that the reason was attributable not to the distribution of the transit service itself but rather to the distribution of destinations. We tested this hypothesis by dividing the study area into groups based on transit demand and comparing their average distance to commuting destinations. The result showed that neighborhoods with higher transit demand (all seven variables) had a longer average distance to jobs, indicating

an inequitable distribution of destinations. These results indicated that merely enhancing transit services cannot lead to a fairer transportation system because accessibility is based on both transportation and land use.

Therefore, planners should design interventions that address these two factors, such as incorporating enough affordable housing into TODs.

Second, ODMTS had a significant positive impact on transit equality. It improved the overall accessibility of the transit service area, leading to a more equal distribution of transit services. In addition, the Gini coefficient based on relative accessibility was higher than that based on absolute accessibility for the current transit system, but the opposite was true for ODMTS. This means that the current transit system was less attractive than driving in areas far from the network, but ODMTS's on-demand shuttles would solve this issue, making public transit a more attractive option even in distant areas. Therefore, ODMTS meaningfully contributed to transit equality by reducing the disparity in transit service between neighborhoods close to the transit network and those far from the network.

These findings should provide valuable insights for transportation planners and decision makers in designing a fair and equitable ODMTS. We developed an interactive online portal (<https://geospatial.gatech.edu/transit-equity>) where visitors can adjust accessibility metrics for commuting and noncommuting trips in Atlanta to visualize how equity and equality change across the region. Future research could extend this study by examining the implications of ODMTS in different locations with different land use and transit configurations, as well as by assessing the equity implications of the transit fare policy of ODMTS.

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SUPPLEMENTAL MATERIAL

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NOTES

- 1 The full-scale ODMTS network is expected to serve three counties (Fulton, DeKalb, and Clayton) surrounding the city of Atlanta.
- 2 We conducted the accessibility analysis for both commuting trips and noncommuting trips and found that the two results did not differ significantly. Thus, we report only the result based on commuting trips.
- 3 Our study focused on transit accessibility and equity for commuting trips. However, to test the hypothesis that inequitable improvement in transit accessibility was associated with inequitable distribution of both jobs and other opportunities, we also examined noncommuting distances to several key points of interest using Google Places API. The results for noncommuting trips showed similar implications for equality and equity as those reported for commuting trips.

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